AUTOMATED OPTIMUM DESIGN OF REINFORCED CONCRETE SILO

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By
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to the
DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

JULY, 1973

to

my parents

taramati and banshidhar

CERTIFICATE

This is to certify that the thesis entitled 'AUTOMATED OPTIMUM DESIGN OF REINFORCED CONCRETE SILO' by SHREE PRAKASH is a record of work carried out under my supervision and that it has not been submitted elsewhere for a degree.

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ACKNOWLEDGEMENTS

I would like to express my deep appreciation and gratitude to:

Dr. Mahesh P. Kapoor to whom I am indebted for introducing me to the area of Mathematical Programming and for his sustained interest, continuous guidance, constructive criticism and unending encouragement which were vital to the success of this effort,

Dr. Y.C. Das, Dr. P. Dayaratnam and Dr. A.J. Valsangkar for useful suggestions and informations,

Mr. R.K. Gupta of M/s. Rampur Engineering Co. Ltd., for providing with field design data ,

All the friends and others for the pleasent company I had with them during my stay and specially to Mr. M. Hariharan, B.P. Sahni and U.S.P. Verma for their ever available support,

The staff of Computer Center, IIT Kanpur for providing facilities on IBM 7044-1401 system,

The Government of Bihar for sponsoring me under QIP.,

Mr. S.N. Pandey for the excellent typing,

My wife Mani and daughter Guria for their patience, understanding and lost week ends.

Shree Prakash

July, 1973 (SHREE PRAKASH)

SYNOPSIS

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KANPUR-16

JULY - 1973

Silo is a common storage structure for storing granular materials like food grains. Reinforced concrete silos are preferred over other convensional storage structures because of various reasons, e.g., economy, saving and better preservation of grains.

The design for a R.C. Silo is essentially a labourious trial and error process and cannot be repeated many times by hand computation, thus resulting in general in an uneconomical structure. The forces acting on a silo, e.g., the dead load, the wind load, the earthquake force, and the grain pressures depend directly on the shape and dimensions of the structure. Thus the attempt of an economical design and saving in constructional materials couples itself with the reduction of these forces. Any saving achieved in the cost of R.C. Silo is going to build-up because of the repetitive requirements of this class of structure. Hence, the problem is most suitable as an automated optimum design problem.

A cast-in-situ circular R.C. Silo with conical bottom, supported on a system of ring-girder and columns has been considered in the present work. A mathematical programming problem has been formulated on the basis of Indian Standard Specifications with minimum cost of the material used as the objective function. The SUMT algorithm has been used to seek the optimum solution using the Davidon-Fletcher-Powell Method with Golden Section Search Technique.

Cost reduction and improvement in design over a recently executed field design has been illustrated.

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LIST OF SYMBOLS

A = horizontal cross-sectional area of the stored material.

A_b = equivalent area (or volume per unit length) of helical reinforcement.

A_c = area of compressive reinforcement in girder

A_c = cross-sectional area of concrete excluding reinforcing steel for tension member.

A_{col} = gross area of column-section

A_e = area of equivalent girder in terms of concrete

A_{equ} = area of equivalent section for unit length of the vertical wall

A_k = area of concrete in column core, excluding area of longitudinal reinforcement

A_r = gross cross-sectional area of ring-girder

A_s = area of reinforcing steel

A_{s1}, A_{s2} = hoop and vertical reinforcements for unit length of the vertical wall

A_{sc} = area of compressive reinforcement in column

A_{scl} = percentage of longitudinal reinforcement in column

A_{scs} = percentage of spiral reinforcement in column

A_{sh1} = percentage of meridinal reinforcement in hopper bottom

A_{sh2} = percentage of hoop reinforcement in hooper bottom

A_{sr1} = percentage of upper longitudinal reinforcement in ring-girder.

A_{sr2} = percentage of lower longitudinal reinforcement in ring-girder.

A_{sr3} = percentage of shear reinforcement in ring-girder

A_{sw1} = percentage of hoop reinforcement in vertical wall

A_{sw2} = percentage of vertical reinforcement in vertical wall

A_t = area of tensile reinforcement in girder

A_w = cross-sectional area of stirrup legs effective in shear

Contd. List of Symbols

Aw_1 = stirrup reinforcement required in shear

Aw_2 = stirrup reinforcement required in torsion

a_1, a_2 = dimensions used for defining actual cross-section of ring-girder (Fig. 6).

B_r = width of equivalent ring-girder

b_1, b_2 = dimensions used for defining actual cross-section of ring-girder (Fig. 6)

C_c = cost of concrete per unit volume

C_{cov} = effective cover to spiral reinforcement in column

Cov = effective cover to girder reinforcement

C_r = stress reduction co-efficient for long column

c = compressive stress on extreme girder-fibre

c_1, c_2, c_3 = reduced stresses for long column (i.e. C_r times the permissible stresses σ_c, σ_{cb}, f_{sh})

c' = torsional rigidity

D = internal diameter of the circular silo

D_{col} = diameter of supporting column

D_h = diameter of a hopper ring section under consideration

D_{open} = diameter of outlet opening

D_{ropen} = diameter of opening for filling

d = effective depth of girder

E_c = modulus of elasticity for concrete

E_{col} = modulus of elasticity for concrete used in column

El_{fact} = effective length factor for column

E_r = modulus of elasticity for concrete used in ring-girder

E_s = modulus of elasticity for steel.

Contd. List of Symbols

e	=	eccentricity of meridional force with the centroid of ring-girder
e_n	=	eccentricity of thrust on girder with neutral axis
e_x	=	eccentricity of thrust on girder with centre line of girder
F_c	=	reduced compressive strength $= C_r\ f_c$
F_h	=	lateral load shared by one column $= F_{horz/NSC}$
FH_{des}	=	hoop force for hopper design
F_{horz}	=	lateral load (maximum of wind or seismic force) on silo
FM_{des}	=	meridional force for hopper design
f_c	=	compressive strength of concrete cube at 28 days
f_s	=	permissible tensile stress in steel*
f_{sh}	=	permissible stress in helical reinforcement*
f_{ss}	=	allowable tension in shear reinforcement*
f_{s1}, f_{s2}	=	allowable tensile stresses in silo reinforcements*
g	=	acceleration due to gravity
H	=	height of the silo wall
H_A	=	concentrated interacting force for ring-girder and column
H_c	=	actual height of the column $= V_{cl} + H_{hop} - H_r$
H_{clear}	=	additional height of the vertical wall for filling
H_{col}	=	effective height of column $= El_{fact} \cdot H_c$
H_{hop}	=	height of conical hopper
H_r	=	height of ring-girder
H_{vw}	=	height of vertical wall $= H$
h	=	total height of silo from top of vertical wall to bottom of hopper (Fig.4).

h_r = rise of the conical roof hopper

I_{col} = moment of inertia of gross column area

I_e = moment of inertia of equivalent girder cross-section

I_r = moment of inertia of gross ring-girder area

j = lever-arm coefficient for girder section

M_T = twisting moment

M_{TA} = concentrated interacting moment for ring-girder and column

M_t = uniform twisting moment on the ring-girder=S.e

m = modular ratio = $2800/f_c$

N = n/H_r

NSC = no. of supporting columns

n = depth of neutral axis

P_{des} = hoop force for vertical wall design

P_h = lateral pressure on bin (silo) wall

P_n = normal pressure

P_v = vertical pressure on horizontal cross-section of stored material

P_w = vertical load transferred to walls due to friction between the stored material and silo wall

p = pitch or spacing of reinforcement

Q = shear force at a cross-section

q,q' = shear stresses in a girder due to transverse shear force and torsional moment respectively

R = hydraulic radius of a silo section = A/U

R_1, R_2 = radii of hopper shell

r = penalty parameter

r_m, r_1,r_2 = mean, internal and external radius of ring-girder

S = force transfered from hopper to ring-girder

S_x, S_y = net horizontal and vertical force per unit length on ring-girder periphery

S_{sg} = maximum compressive stress in concrete of the vertical wall due to frictional load

S_{sh} = maximum bending stress in concrete of the vertical wall

S_{sw} = compressive stress in concrete of the vertical wall due to self weight and load coming from the roof.

S_t = net tensile stress in concrete in the girder

T_{ff} = total frictional load on unit peripherial wall length

T_h = thickness of hopper

T_r = thickness of roof slab

T_w = thickness of vertical wall

T_1,T_2 = meridional and hoop force respectively

t = stress in tensile reinforce of a girder

U = interior perimeter of silo

V_{cl} = clearance (from column base to hopper opening)

W_h = weight of hopper bottom

W_{hg} = weight of grain in hopper

W_r = self weight of ring-girder

W_s = self weight of hopper slab per unit area

W_T = total weight of the silo and stored material on the ring-girder

W_{top} = load from roof to unit peripherial length of the silo wall

W_{wall} = self-weight of the vertical wall per unit peripherial length

w = unit weight of stored material

w_c = unit weight of concrete

x, y = side length of stirrups

z = depth below the level surface of fill

α = angle the hopper bottom makes with horizontal

α_1, β_1 = numerical factors for calculating torsional properties

θ = angle the plane of rupture makes with horizontal

θ_r = angle the roof slab makes with horizontal

ϕ = angle of internal friction for stored material

ϕ' = angle of wall friction

λ = pressure ratio $= P_h/P_v$

λ_e, λ_f = pressure ratio during filling and emptying respectively

μ = tan ϕ

μ' = tan ϕ'

μ'_e = tanϕ'_e

μ'_f = tan ϕ'_f

ϵ_s = shrinkage coefficient for concrete

σ_c = permissible stress for concrete in direct compression*

σ_{cb} = permissible compressive stress for concrete in bending*

σ_s = permissible stress for concrete in shear*

σ_t = permissible stress for concrete in direct tension*

σ_{tb} = permissible tensile stress for concrete in bending*

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* The symbol for permissible stress added with a superscript (') has been used as a symbol for actual stress e.g., f'_s denotes the actual tensile stress in steel.

CHAPTER I

AUTOMATED OPTIMUM DESIGN OF REINFORCED CONCRETE SILO

1.1 INTRODUCTION:

Silo is a common storage structure for storing granular materials like food grains. The substantial losses suffered in the food output because of improper or no storage facilities have warranted the attention of our country to construct a large number of medium sized economical silos. It is this consciousness at the national front which has motivated the present work.

Silos are preferred over other conventional storages because 1) they are moisture-proof, vermin-proof and insect-proof, 2) they provide the maximum space utilization per tonne of the stored material thereby reducing the storage cost, 3) they preserve the quality of the sotred material, and 4) they entail no loss of the stored material while filling and emptying (in handling).

Reinforced concrete is preferred as a constructional material for silo because 1) it is economical, 2) it is fire-proof, and 3) the quality of food grain is better preserved.

Reinforced concrete silos are constructed in different ways(1)*:

(i) Construction in hollow blocks,
(ii) Pillar and panel construction,
(iii) Staves silo construction,
(iv) Pre-cast ring silos, and
(v) Cast-in-situ silos.

The first three methods are suitable for relatively small capacity. Pre-cast ring silos are used for all sizes. Cast-in-situ silos are particularly suitable for medium and large sizes and have been considered in the present work.

The design for a R.C. Silo is essentially a trial and error process where the shape, dimension and reinforcement details are assumed and the stresses are checked for a safe design. Obviously this process cannot be repeated many times by hand computation because of the sheer labour involved, thus resulting

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* Numbers within such brackets indicate the references.

many times in an uneconomical over-designed structure. Any saving achieved in the cost of a R.C. Silo is going to build-up because of the repetitive requirements of this class of structure. Hence, the problem is most suitable as an automated optimum design problem. Furthermore, the forces acting on a silo e.g., the dead load, the wind load, the earthquake force, and the grain pressures depend directly on the shape and dimensions of the structure. Thus any attempt of optimal design towards the saving of the material cost couples itself with the reduction of forces acting on the structure.

1.2 SCOPE OF THE PRESENT WORK:

Here, a circular R.C. Silo with conical (self cleaning) bottom supported on a system of ring-girder and columns as shown in Figs.1 and 2 has been cast as a mathematical programming problem with minimum cost of materials used as the objective function. The adopted design procedure is the one recommended by Indian Standards Specifications[2 and 3].

The loads on a silo have been summarized in the light of IS recommendations[2 and 3], with some emphasis on pressures in silos as suggested by different investigators, in Chapter II.

In Chapter III the analysis and design procedure for R.C. Silo has been presented.

The optimal design formulation for the problem, which turns out to have 15 design variables and 61 constrainsts with cost of materials used for the silo super structure as objective (or merit) function, is described in Chapter IV.

Chapter V discusses in short the optimization seeking methods used for the problem. The Sequential Unconstrained Minimization Technique developed by Fiacco and McCormic giving all the points in the feasible region and thus being of great engineering advantage has been used for converting a constrained problem into an unconstrained one. The Davidon-Fletcher-Powell method with Golden Section Search Technique has been used to seek the solution of the unconstrained minimization problem.

The numerical results have been presented in Chapter VI. Reduction in cost and improvement in design over an existing field design has been shown. Conclusions and scope for future work has also been presented in this chapter.

In any effort of this kind, the development of a computer programme takes the bulk of the effort. The automated optimum design programme of a silo developed in the present work in Fortran language is attached as appendix.

CHAPTER II

LOADS ON THE SILO

2.1 INTRODUCTION:

Silo is a deep bin. Bin is a generic term used for the class of storage structures e.g., bunker or shallow bin and silo or deep bin. The classification of a bin into bunker or silo is based on the pressure exerted by the stored material on to its walls. The plane of rupture of the stored material (defined latter in this chapter) helps this classification. Most significant part of the loads acting on a silo is the pressure exerted by the stored material. Various investigators [4, 5, 6, 7, 8, 9 and 10] and authorities [2,11,12 and 13] have looked into this aspect of silo loading which makes it a subject in itself with substantial background and interesting history. This has been discussed in short in Section 2.3 of this chapter. The other forces acting on a silo are the dead load, wind load, earthquake forces and temperature effects (provided the material stored undergoes a temperature change). All these are described in the subsequent sections in more or less details depending on its earlier documentation.

2.2 DEAD LOAD ON SILO:

The dead loads on silo comprises of the weight of 1) the roof; 2) walls (including partitions, if any); 3) hoppers or floors; and 4) other structural components along with the weight of all other permanent constructions and fixtures as well as the mechanical equipments fitted on the silo for handling of the material.

2.3 LIVE LOADS ON SILO:

Live loads on silo include all loads other than the dead loads and may consist of the following:

i) (a) Live loads on the roof;
   (b) Snow load;

ii) Wind load;

iii) Earthquake load;

iv) Pressures due to stored material; and

v) Loads because of the impact and vibrations due to moving equipments (if any) fitted on the silo.

Indian Standards Specifications[2,3] provide the details of the above live loads on silo and these have been adopted in the present work.

2.3.1 LIVE LOADS ON THE ROOF:

(a) Live load[3] on flat or curved roof with slope upto 10 degrees to which access is provided is taken as 150 kg/m^2 with a maximum of total of 375 kgs. Live load on roof without proper access is taken as 75 kg /cm^2. If slope (θ_r) is greater than 10 degrees (no access is provided), then the live load is computed from the expression:

$$w_r = 75 - 2\,(\theta_r - 10) \qquad (2.1)$$

with a minimum of 40 kg/m^2.

2.3.1(b) Snow Load: If the silo is to be constructed in a region of snow fall, it is designed for the actual load due to snow or for the live load as specified above which ever is more. Actual load due to snow will depend upon the shape of the roof and its capacity to retain snow. The snow load is assumed to be 2.5 kg/m^2 per cm depth of the snow[3]. In the present work snow loads have not been taken into consideration.

2.3.2 WIND LOAD:

The effect of wind is calculated on the basis of basic pressures given in the I.S. Code[3] for entire height of the silo and any projection thereof, having due regard to the variation in pressure with height and

shape factor. The shape factor for circular structures is 0.7[3]. Basic wind pressure can be had from Fig.1A, page VI.1.18 of reference 3 for any height. The value of wind pressure on any structure upto the height of 30 m is 150 kg/cm^2 for Northern India (except for Jammu and Kashmir).

2.3.3 EARTHQUAKE LOAD:

Earthquake shocks cause a movement of ground on which the structure is situated resulting into the vibration of structures located on it. The intensity of ground shock at any location depends upon the magnitude of earthquake, the distance of the epicentre, duration of ground motion and nature of foundation. The response of structure subject to such ground shock depends on material, form, size and mode of construction of the structure.

Design acceleration has been specified by I.S. Code[3] for structures standing on soils which will not settle considerably or slide appreciably due to vibrations lasting for a few seconds. Seismic coefficient (α_h) and factor (F) (Page VI.1.13,16 and 17 of reference 3) which depend upon seismic zones is multiplied by another factor β(Table 5, Page VI.1.14 of reference 3)

depending on the soil foundation system. The seismic zones for India has been shown in Fig. 13, Page VI.1.22 of reference 3. For zone III the values of α_h and F are 0.04 and 0.3 respectively. For raft foundation the value of factor β is 1.0. As food grain storage structures are of post-earthquake importance, seismic coefficients and factor F as obtained above **are** further multiplied by a factor of 1.5[3]. For concrete structures the percentage of damping is taken as 5-10[3].

In the present work the earthquake force has been considered as an equivalent static force acting at mid-height of the silo wall. The system has been idealized as a vertical cantilever with lumped mass of w_T/g at the free end. The equivalent stiffness is given by:

$$K_{eq} = NSC\ (3\ E_{col}\ I_{col}/H_c^{\ 3}) \qquad (2.2)$$

and the natural time period therefore is

$$T_n = 2\pi\ /\sqrt{mass/K_{eq}} \qquad (2.3)$$

For the calculated value of T_n and assumed percentage of damping (5 for the present work); the average

acceleration (Accl.) is obtained from Fig. 15, Page VI.1.16 of reference 3. Finally, the earthquake force turns out to be

$$P_{earthquake} = 1.5 \text{ mass } (\beta.F) \text{ Accl.} \qquad (2.4)$$

2.3.4 PRESSURES DUE TO STORED MATERIALS:

Early designers thought that bulk materials behave like liquid, and designed the storage structures for equivalent liquid pressure. Robert (1882 and 1884) demonstrated with the help of experiments on models and full size silos that the wall pressures donot increase linearly with depth, but part of the weight of stored material is transferred to the walls by friction and consequently, the vertical and horizontal pressures in the lower part of the silo are less than what would be in case filled with liquid. Furthermore he found that the walls are in vertical compression which is certainly not collaborated by a liquid pressure on the walls of the container.

Janssen (1895) and Airy (1897) came with their theories based on statical equilibrium of granular materials. Large amount of experimental work has been conducted and reported by Prante (1896), Bovey (1906), Jamieson (1904),

Lufft (1904) and Pleissner (1906). Ketchum (1909) summarised the state of art in a hand book(14). There he mentions that the lateral pressure due to grain on bin walls is less than the vertical pressure (0.3 to 0.6 of the vertical pressure, depending on the grain etc.) and the increase in this pressure is very little after a depth of $2\frac{1}{2}$ to 3 times the width or diameter of the bin. He further adds that, in case of the moving grain, the pressure is slightly greater than the pressure of grain at rest (maximum variation for ordinary condition is only 10 per cent). From 1909 until 1930 no significant contribution to this study is traceable. It was felt that the problem of pressure distribution in silos was resolved for once and all. However, refinement in the construction materials and improvement in structural design techniques with reduced factor of safety caused failures of many storage structures designed in accordance with the Janssen's or Airy's theory. Theimer(9) has exhaustively reported failures of R.C. Silos, and has rightly mentioned that majority of failures occurred because of operational pressures of storage material , which were much higher than the static pressures on which the designs were based.

Such failures of storage silos all over the world were of much concern among the engineers, and this spurred

new investigations into the loading (pressure distribution) which a granualr material exerts on the storage structures.

Prante's (1896) early observations that pressures varied widely between the initial condition of charging (or filling) and the condition of flow and not constant as claimed by Janssen, Airy and Ketchum, were confirmed experimentally by Takhtamishev (1938-39 and 1941 - USSR), Shumsky (1941 - USSR),Bernstein (1947 - USSR), Reimbert (1943 and 1956-France), Bergau (1959- U.K.), Kim (1959-USSR), Kovtun and Platonov (1959-USSR), Pieper and Wenzel (1964-Germany), Turitzin (1963-USA), Blanchard and Walker (1966-U.K.) etc.

It is of interest to note that some of the early experimental investigations lead to wrong conclusions as they were based on unsophisticated instrumentations. More refined testing indicates that the flow pressure exceeds the initial (or filling) pressure by a factor of 2 to 4 and in some cases the high peak loads occur at higher points also and not only at the base of the silo.

In past 30 to 40 years because of the extensive experimental and theoretical studies, the behaviour of granualr materials have been better understood. This lead to the urgent need for modifying the Janssen's (1895)

and Airy's (1897) classical or Reimbert brothers (1956) moderate theories for silo pressures based on static equilibrium and to account for the dynamic effect in flow condition.

Swiss (Installations d'ensilage, 1956, no. 16[c]), German (Din 1055, Blatt 6, Berlin, 1964), Russian (CH 302-65, Moscow, 1965), Indian (IS:4995-1968) codes and ACI-313 report on bin wall design and construction[13] still use the Janssen formula with little modification here and there to account for the increase in pressure based on the flow concept.

The German[11] and the Indian[2] codes arbitrarily recommend pressure ratios λ_f in filling and λ_e in emptying as 0.5 and 1.0 respectively. They have recommended angle of wall friction (ϕ') equal to K times the angle of internal friction (ϕ) of the stored material. The constant value K suggested, is 0.75 and 0.6 in case of filling and emptying respectively. This is obviously because of the lack of available test data.

The Russian code[12] recommends that, the values of ϕ , ϕ' and λ should be obtained experimentally for the materials in use. To account for discharge condition, they have recommended seperate factors for over-pressure

and serviceability. They have also recommended seperate multiplying factors for exterior and interior bins. Safarian[10] has recommended similar multiplying factors to be used with Janssen and Reimbert pressure schemes. He has suggested and calculated only one factor in place of the two factors given by Russian code.

Theimer[9] has recommended for 50 per cent and 100 per cent increase for interior and exterior silos over Janssen pressure values for some intermediate height. For the rest of the upper and lower part he recommends linear decrease from suggested overpressure to the maximum values suggested by Janssen.

All the above schemes indirectly account for the flow condition by taking some multiplying factor or by increasing the pressure ratio. Walker[7] gave an approximate theory for pressures and arching based on experimental cum theoretical work which accounts directly for flow conditions. However, Jenike and Johanson theory[8] gives the only correct mathematical analysis of the overpressures in flow conditions. They have very clearly pointed to the concentrated reaction at the transition from active to passive state of stress field in silos, to maintain the field equilibrium.

Work is in progress both at the experimental and on the theoretical front and universally accepted design pressure for the silo is yet to be agreed upon.

For the present work, the pressure scheme as per I.S. recommendation[2] has been used as the basis of design, so that the results may be compared with the available field designs. However, the programme developed can easily incorporate any other pressure scheme without difficulty.

2.4 PRESSURE SCHEME USED IN THE PRESENT WORK:

The IS:4995 code for Design of R.C. Bins (Silos) for Bulk Food Grain Storage[2] gives the scheme for pressure on the silo wall and hopper bottom under the assumptions:

a) Material stored in the bin does not undergo volume change during storage.

b) The cohesion for the stored material is too small as compared with the internal friction.

These have been considered in the present work.

2.4.1 PARAMETERS FOR PRESSURE CALCULATION:

The parameters required for calculation of pressure on silo walls are: 1) unit weight (w), 2) angle

of internal friction (ϕ), 3) angle of friction between wall and stored material (ϕ'), 4) pressure ratio (λ), and 5) height to diameter ratio (H/D).

2.4.1(a) Unit Weight (w): - The unit weight of the stored material depends upon many variable factors such as moisture content, particle size and temperature. Consequently, universally applicable values cannot be given. In order to be exact, the actual value should be obtained by test results. However, specifications are given for various materials in Table 2 of reference 2 which has been used in the present work.

2.4.1(b) Angle of internal friction (ϕ): - The angle of internal friction also varies and should be obtained as in case of the unit weight. However, here too, the same table is referred for the present work.

2.4.1 (c) Wall friction (ϕ'): - It is advisable to perform experiments for getting actual values of wall friction. In the present work, the angle of wall friction has been assumed to be 0.75ϕ and 0.6ϕ during filling and emptying respectively as suggested by I.S. Code[2].

2.4.1(d) Pressure ratio (λ): - The ratio of the horizontal to vertical pressures used in the present work are 0.5 and 1.0 during filling and emptying respectively.

The I.S. Code[2] has purposely suggested these values on higher side to account for the over-pressure which exists in the real situation (specially in flow condition).

2.4.1(e) Height to Diameter Ratio: - A silo (deep bin) is a tall structure in which the plane of rupture meets the opposite wall before it emerges out from the top of the filling. The plane of rupture is that surface down which a wedge of material bounded by one wall face, the free surface and the plane of rupture would start to slide, if the boundary walls were to move. The plane of rupture distinguishes the shallow and deep bins (Figs. 3a and 3b) and is vital for pressure calculation on the walls and bottom of bins.

In silos, the entire weight of the material stored is not transferred to the bottom of the structure. A considerable part of this load is resisted by the friction between the material stored and the walls of the storage structure. This results in the reduction of lateral pressure. After certain depth ($2\frac{1}{2}$ to 3 times the width or diameter of the silo), the increase in pressure with depth is very nominal. A silo is preferred to a shallow bin because of the above fact.

Different authorities have suggested different limits on the H/D ratio for deep bin consideration. The I.S. recommendation[2] for classifying a bin as a silo is as follows:

$$H > D \tan \theta \qquad (2.5)$$

where $$\tan \theta = \mu + \sqrt{\mu(1+\mu^2)/(\mu+\mu^2)} \qquad (2.6)$$

In case H/D ratio does not conform to the above equation, the pressure scheme for design consideration shall be taken for a shallow bin. In the present work the latter eventuality does not arise.

2.4.2 PRESSURE CALCULATIONS:

The maximum values of the horizontal pressure on the wall (P_h), the vertical pressure on the horizontal cross-section of stored material (P_v) and the vertical load transferred to the wall per unit area due to friction (P_w) shown in Fig. 4(a) are calculated using the expressions given below in Table 2.1.

TABLE 2.1[2] MAXIMUM PRESSURES

Name of Pressure	During Filling	During Emptying
Maximum P_v	$w.R/(\lambda_f \mu'_f)$	$w.R/(\lambda_e \mu'_e)$
Maximum P_h	$w.R/\mu'_f$	$w.R/\mu'_e$
Maximum P_w	w.R	w.R

2.4.2(a) Variation of Pressure With Depth in Silo: The variation of pressures P_v, P_h and P_w during filling and emptying is obtained from the expression[2]:

$$P_i(z) = (P_i)_{max} \quad (1-e^{-z/z_o}) \tag{2.7}$$

where, P stands for pressure and suffix i stands for v, h or w corresponding to the pressure to be calculated and

$$\left.\begin{aligned} z_o &= R/(\lambda_f \mu'_f) \text{ during filling} \\ &= R/(\lambda_e \mu'_e) \text{ during emptying} \end{aligned}\right\} \tag{2.8}$$

$(P_i)_{max}$ is taken from Table 2.1.

2.4.2(b) Vertical Load on Walls Due to Friction:- The vertical load carried by the wall due to friction between material stored and the wall at any level is equal to the product of the vertical load on the wall (P_w) times the area on which it acts, above that level. It is same as the product of total lateral pressure on the wall above that level (under consideration), and the coefficient of wall friction (μ').

2.4.2(c) Lateral Pressure Near the Bottom of a Silo: To take advantage of the decrease in lateral pressure caused by the presence of the bottom of a silo, the horizontal pressure due to emptying, over a height of 1.2D or 0.75h, which ever is smaller, is taken to be varying linearly from the emptying pressure at this height to the filling pressure at bottom as shown in Fig. 4b(i).

2.4.2(d) Pressure on Hopper Bottom:- The intensity of normal pressure (P_n) at any point on the hopper bottom is taken[2] as

$$P_n = P_v \cos^2\alpha + P_h \sin^2 \alpha + W_s \cos \alpha \qquad (2.9)$$

where P_v and P_h are obtained from eqn. (2.7) with the values of R corresponding to the horizontal section under consideration (Fig. 4.b ii).

2.5 LOAD COMBINATIONS FOR DESIGN CONSIDERATIONS:

To ensure safety and economy in the design of any structure, a judicious combination of the working loads is necessary, keeping in view, the probability of their acting together, their disposition in relation to other loads and the severity of stresses or deformations. In the present work, the combination of loads on silo for design purposes has been taken as follows:-

i) Dead load alone

ii) Dead load + Live load due to storage

iii) Dead load + Lateral load

iv) Dead load + Lateral Load + live load due to storage.

The lateral load means wind or seismic force which ever is severe and has been considered as the equivalent static load acting at the mid-height of the silo.

CHAPTER III

ANALYSIS AND DESIGN OF SILO SUPER STRUCTURE

3.1 INTRODUCTION:

The silo superstructure consists of the following elements:

i) Roof,

ii) Vertical wall or silo wall,

iii) Hopper bottom,

iv) Ring-girder, and

v) Supporting columns.

The procedure for the analysis and design of each of the above element is described in more or less detail depending on earlier documentation and for the sake of completeness of presentation.

The material for construction considered in the present work is reinforced concrete consisting of a concrete mix (M-200) and reinforcing mild steel. It may not be out of place to mention here that I.S. Code[2] specifies to use a concrete mix not leaner than M-200.

3.2 DIMENSIONS OF ELEMENTS:

3.2.1 DIMENSIONS FOR SILO ROOF:-

The roof of the silo is designed as a flat conical dome. The roof thickness is determined to safely

carry the total load (including self-weight of slab, waterproofing material and live load) on it. The meridional force T_1 per unit length is given as

$$T_1 = w_r\ h_r/(2\ \sin^2\theta) \qquad (3.1)$$

and the hoop thrust T_2 per unit length is given as

$$T_2 = w_r\ h_r\ \mathrm{Cot}^2\ \theta \qquad (3.2)$$

Roof thickness (T_r) calculated on the above basis, in general, comes to be too small and thus; is governed by minimum requirement dictated by practical considerations. In the present work, a fixed thickness of 8 cm has been considered. An additional thickness of 2 cm has been accounted for water-proofing material. The slope of the roof is taken as 5^0 and the diameter of the central opening as 30 cm.

3.2.2 DIMENSIONS FOR SILO-WALL:

The overall size of a silo is governed by H/D ratio which depends upon the storage capacity and the material stored. As the increase in pressure with depth is negligible in the lower part of silo wall, the I.S. Code(2) recommends to keep this ratio preferably more than two. In the present work, the parameter (H/D)

is a subject of study. The lower limit on it has been taken as 1.5 to account for the storage of wheat for which the angle of internal friction (ϕ) is 28° and corresponding minimum H/D ratio comes to be 1.4575 and 1.4995 in case of filling or emptying respectively. For a given storage, this ratio is automatically fixed which corresponds to the minimum cost. The internal diameter of the silo (D), has been considered as a design variable in the present work, the height (H) gets fixed-up for a given storage corresponding to the minimum cost design and is calculated as follows (Fig. 2):-

$$H = H_{vw} = (\text{total volume of storage} - \text{volume stored in hopper})/(\pi D^2/4) + H_{clear} \qquad (3.3)$$

where

$$H_{clear} = (D \tan \phi)/4 \qquad (3.4)$$

The thickness of silo wall (T_w) is designed to safely carry all the loads coming on it, the procedure for which is discussed in latter sections. However, as specified by the I.S. Code[(2)], T_w should not be less than the minimum value, T_{min}(cm), obtained from

$$T_{min} = 15 \quad \text{for } D \leq 6 \text{ m} \qquad (3.5)$$

$$= 15 + (D-6)/1.2 \text{ for } D > 6 \text{ m} \qquad (3.6)$$

3.2.3 DIMENSIONS FOR HOPPER BOTTOM:

The hopper bottom for circular silos is in the shape of frustum of a cone. The diameter of the outlet opening (D_{open}) depends upon the desired rate of withdrawl of stored material. In the present work, a constant outlet diameter of 30 cm has been considered. In order that the silo be self cleaning, the hopper angle, α, with the horizontal is to be atleast 10^o more(2) than the angle repose of the stored material. For dry and loose fill, the angle of repose and the angle of internal friction are approximately equal. In the present work, angle α has been taken as 45^o. This is because the angle of internal friction for materials like wheat to paddy vary from 28^o to 36^o. Once the outlet diameter (D_{open}) and the internal diameter of silo (D) are known, the height of the hopper bottom (H_{hop}) is obtained from

$$H_{hop} = \tan \alpha . (D - D_{open})/2.0 \qquad (3.7)$$

The hopper thickness is designed to safely carry the loads coming on it. The design procedure is discussed in latter sections. The minimum limit on it is taken as 15 cm.

3.2.4 DIMENSIONS FOR RING-GIRDER:

The height (H_r) and width (B_r) of the ring-girder supporting the silo and resting generally on equally spaced columns (six in the present work) is designed to safely carry all the loads coming on it from silo as well as for the interacting forces between ring-girder and columns. In the present work, a lower limit of 30 cm on these dimensions has been imposed to accommodate the reinforcements. Because of practical consideration and to use a design table for torsional properties of the section, the ratio of these two dimensions has been taken in between 1 and 4.

The analysis and design procedure adopted for the ring-girder as presented in the latter sections is meant for the idealized equivalent section (Fig. 2).

3.2.5 DIMENSIONS FOR SUPPORTING COLUMNS:

The column height (H_c) is fixed on the basis of clearance required below the hopper outlet and is obtained as follows (Fig. 2):

$$H_c = V_{cl} + H_{hop} - H_r \tag{3.8}$$

The column diameter is designed to safely carry all the loads coming on it through the ring-girder.

The lower limit on the column diameter is taken as 40 cm. This value keeps the ratio of effective length to the lateral dimension of column within 15 (the short column requirement, Section 3.8) for an effective length of the column upto 6 m.

3.3 GENERAL DESIGN CONSIDERATIONS:

The elastic design procedure of reinforced concrete has been used in the present work. Stresses due to drying shrinkage have been considered for members subject to direct tension, viz., vertical wall and hopper bottom. All the elements have been designed on no crack basis (except for the ring-girder with large eccentricity). Sufficient reinforcement has been provided for members in direct tension, designing the same with crack considerations to ensure safety even in the worst case. The stability of vertical wall has been checked after designing it on the basis of strength.

The values of permissible stresses and modulus of elasticity for the constructional materials used in the present work have been also summarised in this section.

3.3.1 STRESSES DUE TO SHRINKAGE:

The shrinkage coefficient, e_s, is taken as 0.0003[2] to account for shrinkage effect and accordingly the permissible

tensile stress in concrete is increased by 33.33 per cent[2] when shrinkage stresses are accounted for.

3.3.2 DESIGN OF A SECTION UNDER DIRECT TENSION:

The silo wall is subject to hoop tension due to lateral pressure (P_h). The hopper bottom is subject to meridional and hoop tension caused by pressures P_h and P_v, the self weight of the hopper and the grain stored in the hopper. These elements are designed on no crack basis. However, sufficient reinforcement is provided at each cross-section so that, if a section cracks due to unexpected operational pressure or lack of supervision at the time of construction, the total tension can be taken by the reinforcing steel only.

If T is the tension per metre length, then the thickness of cross-section (t) is computed as mentioned below:

Actual tensile stress in concrete (σ_t') is given as

$$\sigma_t' = T/(\bar{A}_c + m\,A_s) \leq \sigma_t \qquad (3.9)$$

Substituting, $T = f_s \cdot A_s$ and $\bar{A}_c = 100\ t$

$$f_s\,A_s \leq \sigma_t\,(100\ t + m\,A_s)$$

or,

$$t_{min} = A_s f_s (f_s - m \sigma_t)/(100 f_s \sigma_t)$$

$$= T (f_s - m \sigma_t)/(100 f_s \sigma_t) \qquad (3.10)$$

The expression (3.10) is known as Portland cement formula [15,16] and is derived on no crack basis. The thickness provided should be atleast equal to t_{min} or the minimum thickness specified in section 3.2.

When shrinkage is also accounted the equations (3.9 and 3.10) get modified to

$$\sigma_t' = (T + \epsilon_s E_s A_s)/(A_c + m A_s) \qquad 3.11)$$

and $$t_{min} = T (f_s + \epsilon_s E_s - m \sigma_t)/(100 f_s \sigma_t) \qquad (3.12)$$

3.3.3 STABILITY CONSIDERATION FOR SILO WALL:

In general, silo is a slender structure. In addition to strength considerations, check for stability for vertical wall under different loading conditions is necessary to ensure the safety against buckling failure. Stability of silo wall has been checked in the present work by limiting the compressive stresses as specified by I.S. Code [2]. The compressive stresses are calculated

on the basis of net cross-section (deducting all openings and properly accounting for reinforcement). The total compressive stress calculated on the above basis with lateral load and without lateral load should not exceed 0.2 f_c and 0.15 f_c respectively.

3.3.4 PERMISSIBLE STRESSES AND MODULUS OF ELASTICITY:

The permissible stresses for reinforcing mild steel and concrete (M-200) as used in the present work have been taken from the I.S. Code[2,3] and are as follows:

Particulars	Notation	Permissible stress (kg/cm^2)
i) <u>General Reinforcements:</u>		
Ordinary reinforcement (other than helical)	f_s	1300
Helical reinforcement	f_{sh}	1000
Shear reinforcement	f_{ss}	1250
ii) <u>Silo Reinforcements</u>		
Reinforcement in direct tension Reinforcement in bending tension on exposed face Reinforcement for members less than 22.5 cm in thickness	f_{s1}	1000

	Particulars	Notation	Permissible stress (kg/cm^2)
ii)	Reinforcement for members 22.5 cm or more in thickness (other than those specified above)	f_{s2}	1250
iii)	Concrete (M200)		
	Cube strength of concrete at 28 days	f_c	200
	Bending compression	σ_{cb}	70
	Direct compression	σ_c	50
	Bending tension	σ_{tb}	17
	Direct tension	σ_t	12
	Shear	σ_s	17

The modulus of elasticity of steel (E_s) is taken as 2.1×10^6 kg/cm^2. The modular ratio (m) is obtained as

$$m = 2800/f_c \qquad (3.13)$$

and the modulus of elasticity of concrete (E_c) is obtained as

$$E_c = E_s/m \qquad (3.14)$$

3.4 ANALYSIS AND DESIGN OF SILO WALL:

The wall thickness and hoop reinforcement are designed for hoop force (P_{des}) developed due to the lateral pressure (P_h) and is given as

$$P_{des} = P_h \, D/2 \qquad (3.15)$$

where, P_h is the absolute maximum pressure in either case of filling or emptying and for any point on the wall.

The wall thickness (T_w) is to be designed in such a way that it satisfies the no crack requirement as well as the minimum code requirement as discussed earlier in sections (3.3.2 and 3.2.2).

The hoop reinforcement (A_{s1}) per meter length is calculated treating that the hoop force is taken by steel only and is obtained as follows:

$$A_{s1} = P_{des}/f_{s1} \qquad (3.16)$$

The hoop reinforcement as calculated above should be more than the minimum requirement, i.e., 0.3 per cent[2] of the cross-section.

The vertical reinforcement (A_{s2}) in the silo wall with a minimum of 0.3 per cent[2] is provided, such that the section is sufficient to resist the forces coming on

it in either case, namely 1) empty silo with lateral load, 2) silo full with no lateral load, and 3) silo full with lateral load. Since the bottom most section of the silo wall experiences the maximum stresses, it is this section which is checked. No curtailment of vertical reinforcement is proposed, since, the reinforcement at this root section generally corresponds to near minimum requirement.

The stresses at the root cross-section are calculated as follows:

The compressive stress in concrete due to self weight of the wall and the load on it coming from the roof is given by

$$S_{sw} = (W_{top} + H_{vw} \; T_w \; w_c)/A_{equ} \tag{3.17}$$

where, A_{equ} represents the equivalent area per meter length of the perimeter of the ring and is given as:

$$A_{equ} = T_w + (m-1) \; A_{s2} \tag{3.18}$$

The compressive stress in concrete due to the frictional load coming on the wall due to stored material is given by:

$$S_{sg} = T_{ff}/A_{equ} \tag{3.19}$$

where, T_{ff} is the total maximum frictional load on unit peripherial length of silo wall and is given by:

$$T_{ff} = (H_{vw} - H_{clear}) \; w - P_v \; D/4 \tag{3.20}$$

where, P_v is the vertical pressure on the horizontal cross-section of the stored material at the junction point of the vertical wall and hopper.

The lateral load ($F_{horz.}$), maximum of the equivalent static earthquake force and the wind force, is considered to be acting at mid height of the silo wall. Therefore, the maximum bending stress is obtained as:

$$S_{sh} = D(F_{horz.} H_{vw})/(I_{equ} 4) \qquad (3.21)$$

where, I_{equ} represents the approximate moment of inertia of the equivalent ring and is given by

$$I_{equ} = \pi D^3 \; (T_w + (m-1) A_{s2}) \; /8$$

The combination of these stresses are considered to correspond to the above said loading conditions and accordingly the following cases are checked to ensure that the stresses are within the limit:

i) Empty silo with lateral load: For no crack the relation

$$S_{sh} - S_{sw} \leq \sigma_t \qquad (3.22)$$

is to be satisfied.

ii) Silo full with no lateral load: The stability consideration resulting into the reduced stress check as

per section 3.3 is satisfied by:

$$S_{sw} + S_{sg} \leq 0.15\ f_c \qquad (3.23)$$

iii) Silo full with lateral load: In this case also the stability consideration as per section 3.3 is satisfied by:

$$S_{sw} + S_{sg} + S_{sh} \leq 0.2\ f_c \qquad (3.24)$$

3.5 ANALYSIS AND DESIGN OF HOPPER BOTTOM:

The conical hopper bottom is designed to safely with-stand the meridional force (T_1) and hoop force (T_2).

Total meridional tension (T_1) per unit length of the periphery of the hopper bottom is obtained by considering the vertical equilibrium of forces at that level (Fig. 5a) and is given as:

$$\pi D_h \quad T_1 \text{ Sin } \alpha = \pi D_h^2 \ P_{v/4} + W_{hg} + W_h \qquad (3.25)$$

In the present work the meridional force (FM_1) at the junction of the hopper and vertical wall and the meridional force (FM_2) at mid hopper height are calculated. The maximum of these two forces per unit length is taken as the design force (FM_{des}). The meridional reinforcement and the thickness of hopper bottom are computed exactly the same way

as the case of vertical wall subject to P_{des}.

Referring to Fig. 5(b), the hoop force (T_2) per unit length is obtained from the equilibrium equation:

$$T_1/R_1 + T_2/R_2 = P_n \tag{3.26}$$

For a flat conical hopper, R_1 is infinite and R_2 is $D_h/(2 \operatorname{Sin} \alpha)$. So the hoop force is given by

$$T_2 = P_n \ R_2 = (P_n \ D_h)/(2 \operatorname{Sin} \alpha) \tag{3.27}$$

In the present work, the hoop force at the junction of the hopper and vertical wall and at mid hopper height are calculated. The maximum of these two forces per unit length is taken as the design force (FH_{des}). The reinforcement is computed and the thickness is checked in the manner similar to one described earlier.

The meridional and hoop reinforcements provided in the hopper bottom should not be less than the minimum requirements, i.e., 0.3 per cent of the cross-section[2].

3.6 EVALUATION OF INTER-ACTING FORCES BETWEEN RING GIRDER AND COLUMNS:

The analysis of the sub-structure consisting of the circular ring-girder and equally spaced supporting columns, forming a staging or supporting structure for the silo

has been presented on the basis of Safarian's work[17]. Assumptions have been made to simplify the analysis, viz., 1) the pentagonal section of the ring-girder is replaced by an equivalent rectangular cross-section having the same area and the same centroid (Fig. 6); and 2) the centroidal axes of the columns are assumed to pass through the centroid of the equivalent section of the ring-grider and with the mean diameter circumference of the silo wall cross-section. In otherwords the silo wall, the ring-girder and the columns are not placed eccentric to each other.

3.6.1 EQUIVALENT SECTION OF THE RING-GIRDER:

The gross cross-sectional area of the ring-girder (A_r) is given by

$$A_r = a_1 b_1 - a_2 b_2/2.0 \tag{3.28}$$

The coordinates of the centroid of the pentagon from the origin O (Fig.6) are given as

$$X_1 = \left\{ a_1 b_1^2/2 - (a_2 b_2/2)(b_1 - b_2/3) \right\} / A_r \tag{3.29}$$

and $$Y_1 = \left\{ a_1^2 b_1/2 - (a_2 b_2/2)(a_1 - a_2/3) \right\} / A_r \tag{3.30}$$

The height (H_r) and width (B_r) of the equivalent rectangular cross-section is given by

$$H_r = 2Y_1 \tag{3.31}$$

and $$B_r = A_r/H_r \tag{3.32}$$

3.6.2 LOADS ON THE RING-GIRDER AND COLUMNS:

As shown in Fig.6, the force S which is equal to the meridional tension, FM_1, coming from hopper to the ring-girder, can be resolved in horizontal and vertical components as S'_x and S'_y. The net unit horizontal force (S_x), the total unit vertical load (S_Y) and the uniform torsional moment (M_t) shown in Fig. 6 and acting on the ring-girder are obtained as follows:

$$S_x = S'_x - P_h \tag{3.33}$$

$$S_Y = S'_Y + (W_{top} + W_{wall} + T_{ff} + W_r) \tag{3.34}$$

$$= W_T / (2\pi\, r_m) \tag{3.35}$$

and $$M_t = S\ e \tag{3.36}$$

where, $$e = (H_r + T_w \operatorname{Sin} \alpha - T_h)/2 \tag{3.37}$$

The basic supporting frame with loads coming on it is shown in Fig. 7(a). The free-body sketches showing inter-acting forces on ring-girder and column

are given in Fig. 7(b). These inter-acting forces are obtained by satisfying compatibility as follows:

i) Deflection of ring-grider = Deflection of column

or, $\Delta'_A + \Delta''_A = \Delta'''_A$ (3.38)

where Δ'_A is the deflection of ring due to S_x (always positive),

Δ''_A is the deflection of ring due to H_A (positive for the direction shown in Fig. 7b).

and Δ'''_A is the deflection of column due to H_A and M_{TA} (positive inward).

ii) Rotation of ring-girder = Rotation of column

or $\theta'_A + \theta''_A = \theta'''_A$ (3.39)

where, θ'_A is the rotation of ring-girder due to the applied moment M_t (always positive),

θ''_A is the rotation of ring-girder due to M_{TA} (negative for M_t as shown in Fig. 7),

and θ'''_A is the rotation of column due to H_A and M_{TA} (positive for M_{TA} as shown in Fig. 7b).

The expressions for the various displacements and rotations described above are given below(17):

1) The uniform radial displacement Δ'_A of the circular ring-girder due to uniform horizontal force S_x is obtained by hook's law as:

$$\Delta'_A = S_x \ r_m^2/(A_r \ E_r) \tag{3.40}$$

2) The radial displacement Δ''_A of circular ring-girder at the point of force application for any number of equally spaced equal forces, H_A is given as:

$$\Delta''_A = (H_A \ r_m^3 \ K') \ / \ (2 \ E_r \ I_r) \tag{3.41}$$

The value of K' is calculated corresponding to the value of ϕ_1 (Fig. 8) from the expression:

$$K' = \left\{ \phi_1/2 + (\mathrm{Sin}\ \phi_1 \ \mathrm{Cos}\ \phi_1)/2 \right\} 1/\mathrm{Sin}^2\phi_1 - 1/\phi_1 \tag{3.42}$$

$$= 0.003364 \text{ for six columns as } \phi_1 = \pi/6.$$

The value of K' for any other set of columns, e.g., 4, 8, 10, or 12 are given in Table 3.1.

3) The angle of rotation θ'_A of the circular ring-girder of uniform rectangular cross-section subject to uniformly distributed twisting moment, M_t, along its centre line is given as:

$$\theta'_A = (12\ M_t\ r_m) / (E_r\ H_r^3\ l_n\ (r_2/r_1)) \tag{3.43}$$

4) The angle of rotation θ''_A of the support points of the ring-girder due to interacting moment M_{TA} at each support is determined using superposition of the values for pairs of equal and diametrically opposite applied moments. Fig. 9 shows a ring-girder with one pair of such moments.

The bending and torsion at any section of this ring (Fig. 9) are given as:

$$(M_b)\ \phi_2 = (M_{TA}\ \mathrm{Cos}\ \phi_2)/2.0 \tag{3.44}$$

and
$$(M_T)\ \phi_2 = (M_{TA}\ \mathrm{Sin}\ \phi_2)/2.0 \tag{3.45}$$

The angle of rotation at any section of the ring (Fig. 9) is given as:

$$\theta_{\phi 2} = \frac{M_{TA}\ r_m}{8\ c'} \left[\phi_2 - \frac{\mathrm{Sin}\ 2\ \phi_2}{2} \right] \tag{3.46}$$

where, $0 < \phi 2 \leq \pi/2$

At the either support ϕ_2 is $\pi/2$ and accordingly the angle of rotation is given by

$$\theta_{\pi/2} = (M_{TA}\ r_m\ \pi)/(16\ c') \tag{3.47}$$

Consequently, the general expression for the angle of rotation θ_A'' at the support for various numbers of diametrically opposite moments is given as

$$\theta_A'' = (M_{TA} \; r_m \; \pi K'')/(16 \; c') \tag{3.48}$$

where, K'' is a numerical factor and its value is calculated on the principle of superposition depending on the number of supports (Fig. 8). The value of the coefficient K'' for six columns is calculated below:

$$\frac{\pi}{2} \; K'' = \left[\phi_1 - \frac{\sin 2\phi_1}{2}\right]_0^{\pi/2} + 2\left[\phi_1 - \frac{\sin 2\phi_1}{2}\right]_0^{\pi/6}$$

or, $\frac{\pi}{2} \; K'' = \left(\frac{\pi}{2} - 0\right) + 2\left(\frac{\pi}{6} - \frac{\sqrt{3}/2}{2}\right)$

or, $K'' = 1.1153$

The value of K'' for any other set of columns, e.g. 4, 8, 10 or 12 are given in Table 3.1.

TABLE 3.1[17] NUMERICAL COEFFICIENTS K' AND K''

No. of supports	K'	K''
4	0.012159	1.0000
6	0.003364	1.1153
8	0.001387	1.3633
10	0.000701	1.6199
12	0.000404	1.8972

5) The horizontal displacement Δ'''_A and the angle of rotation θ'''_A at top of the column are calculated treating the same as a cantilever. Therefore,

$$\Delta'''_A = -\frac{H_A \; H_c^3}{3 \, E_{col} \; I_{col}} + \frac{M_{TA} \; H_c^2}{2E_{col} \; I_{col}} \tag{3.49}$$

and
$$\theta'''_A = -\frac{H_A \; H_c^2}{2 \, E_{col} \; I_{col}} + \frac{M_{TA} \; H_c}{E_{col} \; I_{col}} \tag{3.50}$$

Substituting the values of Δ'_A, Δ''_A and Δ'''_A in equation (3.38) and the values of θ'_A, θ''_A and θ'''_A in equation (3.39) we get:

$$\frac{S_x \; r_m^2}{A_r \; E_r} + \frac{H_A \; r_m^3}{2E_r \; I_r} K' = -\frac{H_A \; H_c^3}{3E_{col} \; I_{col}} + \frac{M_{TA} \; H_c^2}{2E_{col} \; I_{col}} \tag{3.51}$$

and
$$\frac{12 \; M_t \; r_m}{E_r \; H_r^3 \; \ln(r_2/r_1)} + \frac{M_{TA} \; r_m \; \pi}{16 \; c'} K''$$

$$= -\frac{H_A \; H_c^2}{2E_{col} \; I_{col}} + \frac{M_{TA} \; H_c}{E_{col} \; I_{col}} \tag{3.52}$$

Putting the value of torsional rigidity, c', as

$$c' = G_c J_r = (0.425.\ E_r)\ (\ \alpha_1\ B_r^4\ ) \qquad (3.53)$$

and taking same value for modulus of elasticity of concrete used for the ring-girder and for columns (i.e. $E_r = E_{col}$), the above equations simplify to

$$\left(\frac{r_m^3}{2I_r}\ K' + \frac{H_c^3}{3I_{col}} \right) H_A - \frac{H_c^2}{2I_{col}}\ M_{TA} = - \frac{S_x\ r_m^2}{A_r} \qquad (3.54)$$

$$\text{and}\ \frac{H_c^2}{2I_{col}}\ H_A + \left(\frac{r_m\ \pi}{6.8\ \alpha_1\ B_r^4}\ K'' - \frac{H_c}{I_{col}} \right) M_{TA} = - \frac{12\ M_t\ r_m}{H_r^3\ \ln(r_2/r_1)}$$

$$(3.55)$$

where, α_1 is the torsional coefficient for the rectangular cross-section and is given in Table 3.2.

The solution of the simultaneous equations (3.54) and (3.55) gives H_A and M_{TA}. The area and moment of inertia of the reinforced concrete cross-section of the ring-girder and the columns used in the above equations are computed in the present work on the consideration of the overall cross-section ignoring the reinforcement.

TABLE 3.2 TORSIONAL PROPERTIES OF RECTANGULAR CROSS-SECTION[17]

Section	Torsional constant m^4	Torsional section modulus and maximum shear stress	Values of coefficients		
			Ratio = $\frac{H_r}{B_r}$	α_1	β_1
		$S_T = \beta B_r^3$	1.0	0.140	0.208
			1.5	0.294	0.346
	$J_r = \alpha_1 B_r^4$	$q'_{max} = \frac{M_{tors}}{S_T}$	2.0	0.457	0.493
			3.0	0.790	0.801
			4.0	1.123	1.150

3.7 ANALYSIS AND DESIGN OF RING-GIRDER:

The ring-girder is a doubly reinforced curved beam. The scheme for the evaluation of thrust, shear force, bending moment and twisting moment at particular sections of the ring-girder, e.g., support point, mid-span point and point of maximum torsion has been presented. A design table has been prepared for the ease in computation of these forces

and moments. This table can be used as a supplement to Table 3 of reference 2. The design procedure for a girder subject to shear and torsion has been presented. Formula has been derived for a doubly reinforced girder subject to bending and axial thrust in terms of non-dimensionalized parameters for the calculation of stresses both for small and large eccentricities. The stresses developed due to forces acting on the girder have been checked against the permissible stresses. The reinforcements provided in the girder have been checked against the sum of the reinforcements required on the basis of balanced section to resist the forces and moments acting on the girder.

3.7.1 EVALUATION OF FORCES AND MOMENTS:

i) The total load (W_T) or the uniform vertical load (S_y) acting on the ring-girder causes bending perpendicular to the plane of the ring-girder and a torsional moment on it. These moments have been determined on the basis of the coefficients[2,17] which are obtained from the Ketchum's equations[14].

ii) The uniform horizontal force (S_x) causes a circumferential thrust which is constant at all cross-section and is equal to S_x r_m.

iii) The uniform twisting moment (M_t) acting on the ring-girder due to the eccentricity of the meridional force transmitted from the hopper to the ring-girder causes bending moment perpendicular to the plane of ring-girder and is equal to $M_t\ r_m$.

iv) The concentrated moment (M_{TA}) acting at the supports subject the ring-girder to bending perpendicular to the plane of the ring-girder and to a torsional moment on it. These values at any cross-section are obtained using the principle of superposition from equations (3.44) and (3.45).

v) The horizontal force (H_A) acting at the supports subject the ring-girder to a bending in the plane of the ring and to a non-uniform circumferential compression. In general, stresses due to the force (H_A) are relatively small[17] and have been neglected in the present work.

The coefficients for vertical shear force, thrust, bending and twisting moment at the supports, mid-spans and at the points of maximum torsion, for a ring-girder supported on 4, 6, 8, 10, or 12 columns have been calculated on the basis of the values given by Safarian[17] and are presented in Table 3.3.

TABLE 3.3** SCHEMATIC TABLE FOR THRUST, SHEARFORCE, BENDING MOMENT AND TORQUE CALCULATION AT VARIOUS AT KEY POINTS IN A SILO RING-GIRDER

No. of supporting cols. NSC	Vertical load on col.	Vertical S.F. due to W_T		Bending Moments					Torsional moment		Angular distance from columns to the point (P_{mt})* of maximum Torsion
		at cols.	at the point (P_{mt})*	Due to W_T		Due to M_{TA}			Due to W_T	Due to M_{TA}	
		$K_1 W_T$	$K_2 W_T$	at col. $K_3 W_T r_m$	at midway between col. $K_4 W_T r_m$	at col. $K_5 M_{TA}$	at midway between cols. $K_6 M_{TA}$	at the point (P_{mt})* $K_7 M_{TA}$	at the point (P_{mt})* $K_8 W_T r_m$	at the point (P_{mt})* $K_9 M_{TA}$	
		K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9	
1	2	3	4	5	6	7	8	9	10	11	12
4	$W_T/4$	.125	.07167	-.03415	0.01762	-.5000	-.7071	-.6366	.0053	.3069	19°12'
6	$W_T/6$	.08333	.04797	-.01482	0.00751	-.8660	-1.0000	-.9549	.00151	.2982	12°44'
8	$W_T/8$	.06250	.03597	-.00827	0.00416	-1.2071	-1.3071	-1.2880	.00064	.2928	9°33'
10	$W_T/10$	.05000	.02884	-.00527	0.00266	-1.5390	-1.6170	-1.5915	.00032	.2916	7° 37'
12	$W_T/12$	.04167	.02403	-.00365	0.00189	-1.8660	-1.9313	-1.9049	.000185	.2505	6°21'

Note- On the ring-girder - the compressive force due to S_x is $S_x r_m$
- the bending moment due to M_t is $M_t r_m$
- the torsional moment due to W_T at the support and mid-span points are zero.

On the ring girder - the vertical shear force dur to W_T at the mid point between columns is zero.
- the bending moment due to W_T at points (P_{mt})*is zero.
- the torsional moment due to M_{TA} at columns and mid span points are $0.5M_T$ and zero respectively.

DESIGN FORCES & MOMENTS:

Compressive force $= S_x r_m$; Vertical shear force $\begin{cases} = K_1 W_T \text{ at the support points} \\ = K_2 W_T \text{ at the points } (P_{mt})^* \end{cases}$

Bending moments $\begin{cases} = K_3 W_T r_m + K_5 M_{TA} + M_t r_m \text{ at the support points} \\ = K_4 W_T r_m + K_6 M_{TA} + M_t r_m \text{ at the mid-span points.} \\ = K_7 M_{TA} + M_t r_m \text{ at the points } (P_{mt})^* \end{cases}$

Torsional Moment $= \begin{cases} K_8 W_T r_m + k_9 M_{TA} & \text{--- at the points } (P_{mt})^* \\ 0.5M_{TA} & \text{--- at the columns (or support points)} \end{cases}$

* Refer to Table column no. 12.

** The coefficients for this Table has been calculated on the basis of Safarian's work(17) to match with the I.S. Code(2). Here, the coefficients K_3, K_4, and K_8 are same as the coefficients K_1, K_2 and K_3 at Table 3 of Ref. 2.

3.7.2 DESIGN OF GIRDER FOR SHEAR AND TORSION:

Shear stresses (q and q') in the girder due to shear force and torsional moment are respectively calculated as

$$q = Q/(\beta_r \; jd) \qquad (3.56)$$

and

$$q' = M_T \;/\; (\beta_1 \; \beta_r^3) \qquad (3.57)$$

where, the coefficient β_1 is to be taken from Table 3.2. If (q + q') is greater than the permissible shear stress (σ_s), shear reinforcements (stirrups) are provided, otherwise not. However, if (q + q') exceeds four times the permissible shear stress in concrete, the section is redesigned.

Reinforcement for shear: If A_{w1} be the area of the reinforcement for shear, the shear resistance developed is given as(3):

$$Q' = f_{ss} \; Aw_1 \; jd/p \qquad (3.58)$$

and consequently the required area of stirrup per unit length for shear force (Q) is obtained as:

$$\frac{Aw_1}{p} = \tilde{A}w_1 = \frac{Q}{f_{ss} \; jd} \qquad (3.59)$$

Reinforcement for torsion:- The area of stirrups (Aw_2) required for a torsional moment (M_T) is given[3] by:

$$\frac{Aw_2}{p} = \widetilde{Aw}_2 = M_T/(0.8\ f_{ss} \times y) \qquad (3.60)$$

In addition to the shear stirrups (Aw_2) longitudinal reinforcements are also provided[3] to take care of the diagonal tension. These reinforcements have the same volume per unit length as contained in the corresponding legs of the stirrups and are provided along with the longitudinal reinforcements in addition to those required for bending.

The total stirrup reinforcement provided per unit length is

$$\widetilde{Aw} = \widetilde{Aw}_1 + \widetilde{Aw}_2$$

$$= A_r\ A_{sr3r} \qquad (3.61)$$

3.7.3 DESIGN OF GIRDER FOR BENDING AND AXIAL THRUST:

If P and M be the axial thrust and bending moment respectively the eccentricity is given by

$$e_x = M/P \qquad (3.62)$$

This eccentricity is termed as small or large depending on whether it is smaller or greater than one sixth times the depth of the girder.

In case of small eccentricity complete section is supposed to be effective and the design is carried out on no crack basis. The centre of gravity line for the section is calculated by equating the moment of the equivalent area on both the sides of this line (Fig. 10a).

$$B_r\, n^2/2 + (m-1)\, A_c\, (n-Cov) = (H_r - n)^2\, B_{r/2} + (m-1)\, A_t\, (H_r - n - Cov)$$

Solving this the depth of the neutral axis is obtained as:

$$n = \frac{Cov(m-1)\, A_c + H_r^2\, B_{r/2} + (m-1)\, A_t\, (H_r - Cov)}{(m-1)\, A_c + H_r\, B_r + (m-1)\, A_t} \qquad (3.63)$$

Non-dimensionalizing both the sides by putting $N = n/H_r$, $A_{sr1} = A_c/(H_r B_r)$ and $A_{sr2} = A_t/(H_r B_r)$,

the above equation (3.63) simplifies to

$$N = \frac{0.5 + (m-1)\, (A_{sr1}\, Cov/H_r + A_{sr2}\, (1-Cov/H_r))}{1.0 + (m-1)\, (A_{sr1} + A_{sr2})} \qquad (3.64)$$

The equivalent area of the girder shown in Fig. 10(a) is given by

$$A_e = H_r\ B_r + (m-1)\ (A_c + A_t)$$

$$= \left[1.0 + (m-1)\ (A_{sr_1} + A_{sr_2})\right] H_r\ B_r \quad (3.65)$$

The moment of inertia of the equivalent section about centre of gravity line is given by:

$$I_e = B_r\ H_r^3/12 + B_r\ H_r\ \ (H_{r/2} - n)^2$$

$$+ (m-1)\left[A_c (n - Cov)^2 + A_t\ (H_r - Cov - n)^2\right]$$

$$= B_r\ H_r^3 \left[1/12 + (0.5 - N)^2 + (m-1)\left\{A_{sr1} (N - Cov/H_r)^2 + A_{sr2}\ (1 - Cov/H_r - N)^2\right\}\right] \quad (3.66)$$

The compressive stress due to axial thrust is same throughout and is given as:

$$\sigma_c' = P/A_e \quad (3.67)$$

The maximum compressive and tensile stresses due to bending moment are obtained from

$$\sigma_{cb}' = M\ \ N\ H_r/I_e \quad (3.68)$$

and $$\sigma_{tb}^{*} = M\,(1-N)\,H_r/I_e \tag{3.69}$$

respectively.

The net tensile stress due to combined bending and thrust is given by

$$S_t = M\,(1-N)\,H_r/I_e \; - P/A_e \tag{3.70}$$

should not exceed the allowable tensile stress (σ_{tb}) in order that the concrete does not crack. For no compression failure the relation

$$\frac{\sigma_c^{*}}{\sigma_c} + \frac{\sigma_{cb}^{*}}{\sigma_{cb}} \leq 1 \tag{3.71}$$

should be satisfied.

In case of large eccentricity, excessive tensile stress is developed causing cracks in the section and the design is carried out with crack considerations. Here, concrete in the tension zone is neglected. The Fig. 10(b) shows a girder section subject to a load with large eccentricity. The stresses at a point is proportional to its distance from the neutral axis, and is given as:

$$s = \delta .\ y \tag{3.72}$$

where, y = distance of the point from the neutral axis,

and δ = a coefficient of proportionality.

For equilibrium,

total compression - total tension = Thrust on the section

or,

$$\int_0^n B_r \, \delta . y \, dy + (m-1) A_c \, \delta . (n\text{-Cov}) - m \, A_t \, \delta (d - n) = P \quad (3.73)$$

or,

$$P = \delta \left[B_r \, n^2/2 + (m-1) A_c \, (n\text{-Cov}) - m \, A_t (d-n) \right] \quad (3.74)$$

Similarly,

moment of resistance = bending moment

or, total moment of the induced compressive and tensile stresses about the neutral axis } = bending moment

$$\text{or, } B_r \frac{n^2}{2} \delta . (2/3)n + (m-1) A_c \, \delta . (n\text{-Cov})^2 + m \, A_t (d-n)^2 . \delta = P \, e_n \quad (3.75)$$

Non-dimensionalizing both the sides, the equation (3.78) simplifies to

$$N\ (N^2 + B\ N + C) - A = 0$$

or $$N = A/(N^2 + B\ N + C) \tag{3.79}$$

where,

$$A = 6\Big[\Big\{(m-1)\ A_{sr1}\ Cov/H_r + m\ A_{sr2}\ (1-Cov/H_r\ )\Big\}\ (e_x/H_r - 0.5)$$

$$+ \Big\{(m-1)\ A_{sr1}\ (Cov/H_r)^2 + m\ A_{sr2}(1-Cov/H_r)^2\Big\}\Big]$$

$$B = 3\ (e_x/H_r - 0.5) = 3\ e_x/H_r - 1.5$$

$$C = 6\ \Big\{(e_x/H_r - 0.5)\Big\{A_{sr1}(m-1) + A_{sr2}\ m\Big\}$$

$$+ A_{sr1}\ (m-1)\ Cov/H_r + A_{sr2}\ m\ (1-Cov/H_r)\Big\}$$

The value of N is obtained by iterative technique from equation (3.79).

The total compressive stress and the net tensile stress due to combined bending and thrust is computed as follows:

Taking moment about the tensile reinforcement we get

$$B_r\, n\, (c/2)\, (H_r - Cov - n/3) + (m-1)\, A_c \left(\frac{n - Cov}{n}\right) c\, (H_r - 2\, Cov)$$

$$= P\, (e_x + H_{r/2} - Cov)$$

$$\text{or,} \quad c = \frac{P\, (e_x + H_{r/2} - Cov)}{0.5\, B_r\, n\, (H_r - Cov - n/3) + (m-1) A_c \left(\frac{n - Cov}{n}\right)(H_r - 2\, Cov)}$$

$$= \frac{P\, (e_x/H_r + 0.5 - Cov/H_r)}{B_r\, H_r \left[0.5\, N(1 - Cov/H_r - N/3) + (m-1)\, A_{sr1} \left(1 - Cov/(NH_r)\right)(1 - 2Cov/H_r\right.}$$

(3.80)

The value of c gives the actual maximum compressive stress on the section and this should not exceed the permissible compressive stress in concrete (σ_{cb}).

The maximum tensile stress is calculated from the triangle of stress as follows:

$$\frac{m\, c}{t} = \frac{n}{H_r - Cov - n} = \frac{N}{1 - Cov/H_r - N}$$

$$\text{or,} \quad t = \frac{m\, c\, (1 - N - Cov/H_r)}{N} \qquad (3.81)$$

This value of t should not exceed the allowable tensile stress in steel.

When the girder is subject to negative or hogging moment, the upper reinforcement becomes tensile reinforcement and the lower one becomes compressive reinforcement and accordingly the formulae for calculating the stresses get modified.

3.7.4 REINFORCEMENT REQUIREMENT FOR A BALANCED SECTION:

A balanced or critically reinforced girder section is one in which the extreme concrete fibre in compression and steel in tension reaches their respective permissible stress simultaneously. For a balanced section the coefficients for the depth of the neutral axis (N_{cr}) and the lever arm (J_{cr}) are given as

$$N_{cr} = 1 /(1 + f_s/(m\sigma_{cb}) \qquad (3.82)$$

and $$J_{cr} = 1 - N_{cr}/3 \qquad (3.83)$$

For a balanced section subject to a moment M, the area of tensile steel (A_s) required for reinforcing the section is obtained as

$$A_s = M/(f_s\ J_{cr}\ (H_r - Cov)) \qquad (3.84)$$

As the ring-girder is subject to shear force, twisting moment and bending moment, simultaneously, the

total reinforcement requirements are checked against the reinforcements provided, in all such possible cases. The stirrup reinforcement provided at a section should be atleast equal to the stirrup reinforcement required at that section to safely carry the shear force as well as the torsion as discussed in Section 3.7.2. The longitudinal reinforcement provided at a section should be at least equal to the sum of the reinforcement required due to bending as well as due to torsion. The required reinforcements are calculated with balanced section consideration.

The lower limit on girder reinforcements, viz., upper longitudinal, lower longitudinal and stirrups has been taken as 0.3 per cent of the girder cross-section.

3.8 ANALYSIS AND DESIGN OF COLUMNS:

The silo super structure has been supported on a set of six equally spaced spirally reinforced concrete column in the present work. The design procedure for a spirally reinforced concrete column is discussed. The columns are designed to carry lateral load on the silo with and without the stored material in the silo.

3.8.1 SILO UNDER LATERAL LOAD:

As described earlier, the lateral load considered in the present work is the maximum of the wind or earthquake force, F_{horz}, and acts at the mid-height of the silo. The longitudinal force in the column due to bending effect caused by the lateral load is considered to vary linearly with the distance from the line perpendicular to the wind direction or the direction of earthquake and passing through the centroid of the group of columns. The absolute maximum possible tensile or compressive force which may occur in a column is given by

$$C_{lodh} = \frac{F_{horz.}(H_r + H_{vw}/2)}{r_m \left[2 + 4\,\mathrm{Sin}^2(\pi/6)\right]} \qquad (3.85)$$

In addition to this all the six columns are subject to horizontal force

$$F_h = F_{horz}/6 \qquad (3.86)$$

in the direction of wind or the direction of earthquake.

3.8.1 (a) Silo Full with Lateral Load: - In this case one of the column is subject to maximum compressive force which is given as

$$C_{lod1} = W_T/6.0 + C_{lodh} \tag{3.87}$$

The moment acting on the top of the column is given as

$$C_{bm1} = M_{TA} \tag{3.88}$$

In addition, every column is subject to horizontal forces, H_A and F_h in the radial direction and in the direction of wind or the direction of earthquake respectively as discussed earlier. In a particular case these two horizontal forces are added together. Therefore, the base of the column is subject to a downward load of

$$C_{lod2} = C_{lod1} + w_c A_{col} H_c \tag{3.89}$$

and maximum beinding moment of

$$C_{bm2} = |(H_A + F_h) H_c - M_{TA}| \tag{3.90}$$

3.8.1(b) Empty Silo with Lateral Load:- In this case one of the column is subject to maximum tensile force which is calculated as follows:

The downward load on the column for empty silo is given as:

$$C_{lod3} = (W_T - \text{Weight of total material stored in the silo})/6 \tag{3.91}$$

So, that net tensile force in the column is given by

$$C_{lod\,t} = C_{lodh} - C_{lod3} \tag{3.92}$$

It may be mentioned here that in the case of empty silo the bending moment coming on to the column is in general very small and hence is neglected.

3.8.2 EFFECTIVE LENGTH OF THE COLUMN:

The effective column length (H_{col}) is taken as El_{fact} times the unsupported length of column (H_c). The value of this factor (El_{fact}) depends on the end conditions of the column and is taken in accordance with Table 8, Page VI 5.19 of reference 3. In the present work, the end conditions are considered to be fixed at the base and partially fixed at the top for which El_{fact} has been taken as 0.8.

3.8.3 SHORT AND LONG COLUMN CONSIDERATIONS:

If the ratio of effective length of the column to the least lateral dimension (radius of gyration) is less than 15 (50), the column is termed as short column, otherwise, it is termed as long column.

The permissible stresses in a reinforced concrete long column shall not exceed those which result from the multiplication of the appropriate maximum permissible stresses and the coefficient c_r, obtained from

$$c_r = 1.5 - \frac{H_{col}}{30\ D_{min}} \qquad (3.93)$$

or $$c_r = 1.5 - \frac{H_{col}}{100\ r_{min}} \qquad (3.94)$$

where, D_{min} and r_{min} are least dimension and least radius of gyration respectively.

In the case of short column c_r is taken as one and thus no reduction in permissible stresses is required. In the present work equation (3.93) has been used.

3.8.4 REINFORCEMENTS:

In general, the longitudinal steel reinforcement in a concrete compression member can be in between 0.8 per cent to 8 per cent of the gross cross-sectional area. However, because of practical difficulties like accommodation of reinforcement and to avoid excessive cracking the percentage of reinforcement is limited to 4 only. In the present work the lower and upper limits for longitudinal reinforcement are taken as 0.8 per cent and 4 per cent respectively. For spiral reinforcement these values are taken as 0.3 per cent and 2.3 per cent of the gross cross-section.

3.8.5 PERMISSIBLE LOADS:

For a column with helical reinforcement the actual axial load is not to exceed P which is given by

$$P = c_1 A_k + c_2 A_{sc} + 2 c_3 A_b \qquad (3.95)$$

In addition to this, the sum of the terms $c_1 A_K$ and $2 c_3 A_b$ is also not to exceed $0.5 F_c A_c$.

3.8.6 COLUMN SUBJECT TO COMBINED AXIAL AND BENDING FORCES:

In order to design a column on no crack basis, the column section and its reinforcement are proportioned

such that the compressive stresses satisfy the interaction formula

$$\sigma'_c/\sigma_c + \sigma'_{cb}/\sigma_{cb} \leq 1 \qquad (3.96)$$

where, $\sigma'_c = P/\left[A_c + m\ (A_{sc} + 2\ A_b)\right]$

and $\sigma'_{cb} = M/Z$

where, Z is equivalent modulus of the column cross-section and is given as

$$Z = \left[\pi D^4_{col}/64 + (m-1)A_{sc}(D_{col}-2\ C_{Cov})^2/4\right] \frac{2}{D_{col}}.$$

$$= \pi D^3_{col}/32 + (m-1)\ A_{sc}\ (D_{col}-2\ C_{cov})^2/(2\ D_{col})$$

Furthermore, the resultant tensile stress in concrete is not to exceed 35 per cent and 25 per cent of the resultant compressive stress for biaxial and uniaxial bending respectively. In the present work the column is subjected to uniaxial bending only.

$$\therefore\ \sigma'_{tb} = M/Z \leq 0.25\ (\sigma'_{cb} + \sigma'_c) + \sigma'_c \qquad (3.97)$$

3.8.7 COLUMN SUBJECT TO DIRECT TENSION:

If column is subject to occasional tensile force (C_{lodt}) its diameter and reinforcements are designed to safely carry the same as follows: Considering the column section to be uncracked, the resistive force ($T_{col\ u}$) offered by the section is given by:

$$T_{col\ u} = \sigma_t \left[A_{col} + (m-1)\ (A_{sc} + 2\ A_b) \right] \tag{3.98}$$

Considering that concrete in the column cross-section is cracked, the permissible tension ($T_{col\ c}$) is given by

$$T_{col\ c} = 1.33\ (A_{sc}\ f_s + 2\ A_b\ \ f_{sh}) \tag{3.99}$$

The minimum of these two is taken as the permissible load ($T_{col\ p}$) for the column in Tension and this should be atleast equal to the maximum applied tensile force (C_{lodt}).

In the present work, the column diameter and reinforcements are assumed and stresses are checked so that it may safely with-stand the applied loads coming on to the columns under various conditions of loading as discussed earlier.

CHAPTER IV

FORMULATION OF THE OPTIMAL DESIGN PROBLEM

4.1 INTRODUCTION:

The optimal design problem has been formulated as a mathematical programming problem. A mathematical programming problem consists of minimizing or maximizing an objective function $f(\vec{d})$, subject to certain constraints, $g_j(\vec{d}) \leq, =, \text{or} \geq b_j$; $j = 1, 2, \ldots m$, where $\vec{d}$ is a n-dimensional vector of design variables.

4.2 DESIGN VARIABLES:

In the present work, the design variables considered are as follows:

i) Internal diameter of the silo (D),

ii) Thickness of the vertical wall (T_w),

iii) Thickness of the hopper bottom (T_h),

iv) Height of the ring-girder (H_r),

v) Width of the ring-girder (B_r),

vi) Diameter of supporting columns (D_{col}),

and reinforcement as percentage of cross-section as:

vii) Hoop reinforcement for vertical wall (A_{sw1}),

viii) Vertical reinforcement for vertical wall (A_{sw2}),

ix) Meridional reinforcement for hopper bottom (A_{sh1}),

x) Hoop reinforcement for hopper bottom (A_{sh2}),

xi) Upper longitudinal reinforcement for ring-girder (A_{sr1}),

xii) Lower longitudinal reinforcement for ring-girder (A_{sr2}),

xiii) Stirrups or shear reinforcement for ring-girder (A_{sr3}),

xiv) Spiral or helical reinforcement for column (A_{scs}), and

xv) Longitudinal reinforcement for column (A_{scl}).

So the design vector becomes:

$$\vec{d} = \begin{Bmatrix} d_1 \\ d_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ d_{15} \end{Bmatrix} \equiv \begin{Bmatrix} D \\ T_w \\ T_h \\ H_r \\ B_r \\ D_{col} \\ A_{sw1} \\ A_{sw2} \\ A_{sh1} \\ A_{sh2} \\ A_{sr1} \\ A_{sr2} \\ A_{sr3} \\ A_{scs} \\ A_{scl} \end{Bmatrix} \tag{4.1}$$

4.3 OBJECTIVE FUNCTION:

The objective or merit function provide a measure of usefulness or the basis of comparision between the acceptable designs. In general for the civil engineering structures, cost is of paramount importance. Therefore, the cost of the silo super structure has been considered as the objective function. In order to account for the lift, the cost of materials for every metre lift above a height H_{fc} from the base of the column has been considered to be an additional 1 per cent more than the cost of materials upto the height H_{fc}. The total cost of the silo super structure in terms of the design variable can be expressed as follows:

$$(Cost)_T = (Cost)_C + (Cost)_R + (Cost)_S \quad (4.2)$$

where, $(Cost)_C$ represents the cost of supporting columns,

$(Cost)_R$ represents the cost of ring-girder, and

$(Cost)_S$ represents the cost of silo super structure which consists of the roof, the vertical wall and the hopper bottom.

$$\text{or, } (Cost)_T = C_c \Big[NSC \, \pi \, \frac{D_{col}^2}{4} \Big\{ H_{fc} + (H_c - H_{fc}) (1 + P_{icc}) \Big\}$$

$$\Big\{ 1 + C_{r1} (A_{scs} + A_{scl}) \Big\} \Big]$$

$$+ \; C_c \left[(1 + P_{icr}) \, \pi \, (D + T_w) \, H_r \, B_r \left\{ 1 + C_{r1} \, (A_{sr1} + A_{sr2} + A_{sr3}) \right\} \right]$$

$$+ \; C_c \, \pi \left[\left\{ (1 + P_{icruf}) \left(\frac{D - D_{ropen}}{2} \right) T_r \, \frac{H_{roof}}{\sin\theta_r} \right. \right.$$

$$\left. (1 + C_{r1} \, 2 \, A_{smin}) \right\}$$

$$+ \left\{ (1 + P_{icv}) \, (D + T_w) \, T_w \, H_{vw} (1 + C_{r1} (A_{sws1} + A_{sw2})) \right\}$$

$$\left. + \left\{ (1 + P_{ich}) \, \frac{D - D_{open}}{2} \, T_h \, \frac{H_{hop}}{\sin\alpha} \, (1 + C_{r1} (A_{sh2} + A_{sh2})) \right\} \right] \tag{4.3}$$

where

$$H_{roof} = \tan\theta_r \, (D - D_{ropen})/2$$

$$H_{hop} = \tan\alpha \, (D - D_{open})/2$$

$$A_{smin} = 0.003$$

$$C_{r1} = Cost_r^{-1}$$

$$P_{icc} = (H_c - H_{fc}) \, P_{ic/2}$$

$$P_{icr} = (H_c - H_{fc} + H_{r/2}) \, P_{ic}$$

$$P_{icruf} = (H_c + H_r + H_{vw} - H_{fc} + H_{roof/2}) P_{ic}$$

$$P_{icv} = (H_c + H_r - H_{fc} + H_{vw/2}) \, P_{ic}$$

and $P_{ich} = (H_c + H_r - H_{fc} - H_{hop/2}) \, P_{ic}$

where, $P_{ic} = 0.01$

and $Cost_r$ = ratio of cost for steel and concrete

4.4 CONSTRAINTS:

A design is considered to be safe only when, it performs within certain limits. This imposes certain constraints on the behaviour parameters of the structure which in turn are the functions of the design variables. Such constraints are termed as behaviour constraints. In the present problem there are 24 constraints related with the bounds on the various kinds of stresses developing on the structure. These are grouped as 1 to 24 in the following listing. Over and above the behaviour constraints, there are always limitations appearing on the variables due to constructional and other practical considerations. These are termed as side constraints. In the present problem, all the fifteen design variables have been bounded between the lower and the upper limits thus, contributing to a total of 30 side constraints. These are grouped as 25 to 54 in the following listing. In order to check whether the silo or deep bin condition exist or not, a limit on H/D ratio is checked which correspond to the 55th constraint in the list. Moreover, to ensure the stability of the silo wall, I.S. Specifications[2] put a limit on the wall thickness related with the diameter of the silo. This has been incorporated as the

56th constraint. To facilitate to use of design table for the torsional properties of the ring-girder cross-section (refer section 3.2.4), the upper and lower limit on the ratio of the two sides of the ring-girder has been specified. These form the 57th and 58th constraints. Finally, to ensure the sufficiency of reinforcements in the ring-girder as upper longitudinal, lower longitudinal and stirrups the last three constraints (59 to 61) are incorporated as discussed in section 3.7.4. The various constraint equations and expressions arranged in order are as follws.

1. Tensile stress in concrete of the vertical wall (without shrinkage consideration) due to hoop force is given as

$$\sigma_t' = \frac{P_{des}}{100\ T_w\ (1+(m-1)\ A_{sw1})} \leq \sigma_t' \qquad (4.4)$$

2. Tensile stress in concrete of the vertical wall (with shrinkage consideration) due to hoop force is given as

$$\sigma_t' = \frac{P_{des}\ + \epsilon_s\ E_s\ A_{sw1}\ 100\ T_w}{100\ T_w(1\ +\ (m-1)\ A_{sw1})} \leq 1.333\sigma_t' \qquad (4.5)$$

3) Tensile stress in hoop steel subject to hoop force (considering concrete to be cracked) is given as

$$f'_{s1} = \frac{P_{des}}{A_{sw1}\ 100\ T_w} \leq f_{s1} \qquad (4.6)$$

4) The net tensile stress in concrete of the vertical wall in case of empty silo with lateral load is given as

$$S_{sh} - S_{sw} \leq \sigma_{tb} \qquad (4.7)$$

5) The total compressive stress in concrete of the vertical wall in case of silo full without lateral load is given as

$$S_{sw} + S_{sg} \leq 0.15\ f_c \qquad (4.8)$$

6) The total compressive stress in concrete of the vertical wall in case of silo full with lateral load is given as

$$S_{sw} + S_{sg} + S_{sh} \leq 0.2\ f_c \qquad (4.9)$$

7) Tensile stress in concrete of the hopper bottom subject to meridional force (without shrinkage consideration is given as

$$\sigma_t' = \frac{FM_{des}}{100\ T_h\ (1+(m-1)\ A_{sh1})} \leq \sigma_t \qquad (4.10)$$

8) Tensile stress in concrete of the hopper bottom subject to meridional force (with shrinkage consideration) is given as

$$\sigma_t' = \frac{FM_{des} + \epsilon_s E_s A_{sh1} \, 100 \, T_h}{100 \, T_h \, (1+(m-1) \, A_{sh1})} \leq 1.333 \, \sigma_t \quad (4.11)$$

9) Tensile stress in meridional steel subject to meridional force (considering concrete to be cracked) is given as

$$f_{s1}' = \frac{FM_{des}}{A_{sh1} \, 100 \, T_h} \leq f_{s1} \quad (4.12)$$

10) Tensile stress in concrete of the hopper bottom subject to hoop force (without shrinkage consideration) is given as

$$\sigma_t' = \frac{FH_{des}}{100 \, T_h \, (1+(m-1) \, A_{sh2})} \leq \sigma_t \quad (4.13)$$

11) Tensile stress in concrete of the hopper bottom subject to hoop force with shrinkage consideration is given as

$$\sigma_t' = \frac{FH_{des} + \epsilon_s \, E_s \, A_{sh2} \, 100 \, T_h}{100 \, T_h \, (1 + (m-1) \, A_{sh2})} \leq 1.333 \, \sigma_t' \quad (4.14)$$

12) Tensile stress in hoop steel of the hopper bottom subject to hoop force (considering concrete to be cracked) is given as

$$f'_{s1} = \frac{FH_{des}}{A_{sh2} \quad 100 \quad T_h} \leq f_{s1} \qquad (4.15)$$

13) The sum of the shear stresses in the ring-girder due to shear and torsion at any section is given as

$$q + q' \leq 4 \tau_s \qquad (4.16)$$

14) The compressive stress c (stresses σ'_{cb} and σ'_c) in concrete of the ring-girder subject to combined bending and thrust at mid-span points with large (small) eccentricity is (are) calculated and the following relation is checked.

$$\left.\begin{array}{ll} c \leq \sigma_{cb} & \text{in case with large eccentricity} \\ \dfrac{\sigma'_{cb}}{\sigma_{cb}} + \dfrac{\sigma'_c}{\sigma_c} \leq 1 & \text{in case with small eccentricity} \end{array}\right\} (4.17)$$

15) The net tensile stress $t(S_t)$ in steel (concrete) of the ring-girder subject to combined bending and thrust at mid-span point with large (small) eccentricity is calculated and the following relation is checked.

$t \leq f_{s2}$ in case with large eccentricity
$S_t = \sigma'_{tb} - \sigma'_c \leq \sigma_{tb}$ in case with small eccentricity

(4.18)

16) The compressive stress c (stresses σ'_{cb} and σ'_c) in concrete of the ring-girder subject to combined bending and thrust at support points with large (small) eccentricity is (are) calculated and the following relation is checked

$c \leq \sigma_{cb}$ in case with large eccentricity
$\frac{\sigma'_{cb}}{\sigma_{cb}} + \frac{\sigma'_c}{\sigma_c} \leq 1$ in case with small eccentricity (4.19)

17) The net tensile stress $t(S_t)$ in steel (concrete) of the ring-girder subject to combined bending and thrust at support points with large (small) eccentricity is calculated and the following relation is checked

$t \leq f_{s2}$ in case with large eccentricity
$S_t = \sigma'_{tb} - \sigma'_c \leq \sigma_{tb}$ in case with small eccentricity (4.20)

18) For no tension failure of the column cross-section, C_{lodt} and T_{colp} as discribed in section 3.8.7 should satisfy the relation

$C_{lodt} \leq T_{colp}$ (4.21)

At top section the column is subject to a downward load, a bending moment and a horizontal force. The stresses are calculated on no crack basis and the following relations are checked.

19) $$c_1 A_k + 2 c_3 A_b \nless 0.5 F_c A_c \qquad (4.22)$$

20) $$\frac{\sigma_c'}{\sigma_c} + \frac{\sigma_{cb}'}{\sigma_{cb}} \le 1 \qquad (4.23)$$

21) $$\sigma_{tb}' - \sigma_c' \le 0.25 \, (\sigma_{cb} + \sigma_c) \qquad (4.24)$$

At bottom section of the column also the stresses are calculated on no crack basis corresponding to the forces acting at that section and the following relations are checked.

22) $$c_1 A_k + 2.\ c_3 A_b \nless 0.5 F_c A_c \qquad (4.25)$$

23) $$\sigma_c'/\sigma_c + \sigma_{cb}'/\sigma_{cb} \le 1 \qquad (4.26)$$

24) $$\sigma_{tb}' - \sigma_c' \le 0.25 \, (\sigma_{cb} + \sigma_c) \qquad (4.27)$$

25) to 54) Limits on design variables: The following constraints specify the lower and upper bound on the various design variables,

$$(d_{min})_i \le d_i \le (d_{min})_i, \; i=1,2,\ldots 15 \qquad (4.28)$$

where, $(d_{min})_i$ and $(d_{max.})_i$ are the lower and upper limits on the ith design variable and are given in Table 4.1.

TABLE 4.1 LIMITS ON DESIGN VARIABLES

Variable	Units	Lower Limit	Upper limit
D	m	1.0	9.0
T_w	m	0.15	0.3
T_h	m	0.15	0.3
H_r	m	0.3	1.8
B_r	m	0.3	1.8
D_{col}	m	0.4	1.2
A_{sw1}	per cent of cross-section	0.3	2.3
A_{sw2}	- do -	0.3	2.3
A_{sh1}	- do -	0.3	2.3
A_{sh2}	- do -	0.3	2.3
A_{sr1}	- do -	0.3	2.3
A_{sr2}	- do -	0.3	2.3
A_{sr3}	- do -	0.3	2.3
A_{scs}	- do -	0.3	2.3
A_{scl}	- do -	0.8	4.0

55) Deep silo criterion is given by the equation

$$H/D \geq 1.5 \qquad (4.29)$$

56) Limitation on the wall thickness, for a silo more than 6 m in diameter, is given as

$$T_w \geq 15 + (D-6)/1.2 \qquad (4.30)$$

57) to 58) Limitations on the relative dimensions of the ring-girder are given as

$$1.0 \leq \text{Ratio} \leq 4.0 \qquad (4.31)$$

where,

$$\text{Ratio} = \frac{\text{Maximum of } H_r \text{ and } B_r}{\text{Minimum of } H_r \text{ and } B_r}$$

59) to 61) The total reinforcement (percentage of cross-section) required for the ring-girder as upper and lower longitudinal reinforcement and stirrups as discussed in section 3.7.4 are calculated as A_{sr1r}, A_{sr2r} and A_{sr3r}. The relations

$$A_{sr1r} \leq A_{sr1} \qquad (4.32)$$

$$A_{sr2r} \leq A_{sr2} \qquad (4.33)$$

$$A_{sr3r} \leq A_{sr3} \qquad (4.34)$$

are checked for sufficiency of reinforcements.

4.5 NORMALIZATION OF DESIGN VARIABLES:

All the design variables are normalized such that they lie in a range of 0 to 1. Thus if d_i, $(d_{min})_i$ and $(d_{max})_i$ denotes the actual value, the lower and the upper bound for the ith design variable, then the normalized variable $(D_n)_i$ is given as

$$(D_n)_i = \frac{d_i - (d_{min})_i}{(Span)_i}, \quad i=1,2, \ldots, 15 \tag{4.35}$$

where, $(Span)_i = (d_{max})_i - (d_{min})_i$

Such a normalization puts equal weightage to all design variables during the course of search for minimum design. The normalized variables are non-dimensional.

4.6 NORMALIZATION OF CONSTRAINT EQUATIONS:

The constraint equations are also normalized with an identical aim as that for design variables. Typical examples of normalizing a behaviour and a side constraint is given below:

A behaviour constraint is typically represented as

$$\sigma_t' \leq \sigma_t \tag{4.36}$$

which can be rewritten as

$$\sigma_t - \sigma_t' \geq 0$$

dividing both the sides by σ_t we get the normalized constraint as

$$g_j = 1 - \sigma_t'/\sigma_t \geq 0 \tag{4.37}$$

A side constraint is typically represented as

$$(d_{min})_1 \leq d_1 \leq (d_{max})_1 \tag{4.38}$$

Taking first part of the inequality and dividing by $(Span)_1$ we have

$$\frac{d_1 - (d_{min})_1}{(Span)_1} \geq 0$$

or, $\quad (D_n)_1 \geq 0 \qquad (4.39)$

Considering other part of the inequality and dividing by $(Span)_1$ we get

$$\frac{(d_{max})_1 - d_1}{(Span)_1} \geq 0$$

The above equation can be rewritten as:

$$\frac{(d_{max})_1 - (d_{min})_1 - \left\{ d_1 - (d_{min})_1 \right\}}{(Span)_1} \geq 0$$

or, $$1 - (D_n)_1 \geq 0 \qquad (4.40)$$

Both equations (4.39) and (4.40) are satisfied, if we satisfy only one equation given by

$$g_j = (D_n)_1 \left[1 - (D_n)_1 \right] \geq 0$$

In this way all the constraints subject to upper and lower bounds are reduced to only one. There are 16 such constraint equations in the present problem.

The normalization of the constraints as discussed above effectively has reduced the number of constraint equations to 45.

4.7 NATURE OF THE OPTIMAL DESIGN PROBLEM:

Since the objective function and the behaviour constraints are non-linear functions of the design variables, the optimal design problem of the silo as formulated above is a non-linear programming problem. The method for seeking the solution of this non-linear programming problem is discussed in the next chapter.

CHAPTER V

OPTIMUM SEEKING METHOD

5.1 INTRODUCTION:

The optimum design of the silo structure has been formulated in the previous chapter as a non-linear mathematical programming problem which is of the form:

Find $\vec{d}$, such that, $f(\vec{d})$ is a minimum,

subject to $g_j(\vec{d}) \geq 0$, $j = 1, 2, \ldots m$.

If n be the order of the design vector, then in the n-dimensional search space, there will in general be a number of design points (set of design variables) which will satisfy all the constraint equations and this chapter deals with the algorithm of picking up the best design corresponding to which the value of $f(\vec{d})$ is minimum.

Many algorithms are available to seek the solution of a non-linear mathematical programming problem. These can be classified as:

i) Direct methods in which the constraint equations are handled explicitly. Well-known algorithms of this class are 1) Zoutendijk's Method, and 2) Rosen's Gradient Projection Method.

ii) Indirect methods in which the constraint equations are implicitly satisfied. A class of algorithms called Penalty Function Method is well-developed in this category. This has been widely used with success on a large class of problems.

Picking a method is by and large an art. This mainly depends on the type of the problem and the tools readily available in hand. For the present work, the Interior Penalty Function Method which has advantage of giving all points in the feasible or acceptable region, and thus advantageous from engineering point of view, has been used. The SUMT algorithm which pertains to this class has been described in short.

5.2 SEQUENTIAL UNCONSTRAINED MINIMIZATION TECHNIQUE

The technique of optimal solution seeking, developed by Fiacco and McCormick[18], known as the Sequential Unconstrained Minimization Technique (SUMT) is an Interior Penalty Function Method. In this method the constrained problem is transformed into an unconstrained problem by appending the constraints to the objective function through a penalty parameter r. This gives some sort of a high imaginary wall at the constraint surface

which does not permit crossing-over into the infeasible domain. The resulting function, $F(\vec{d}, r)$, known as penalty function is given as

$$F(\vec{d}, r) = f(\vec{d}) + r \sum_{j=1}^{m} \frac{1}{g_j(\vec{d})} \tag{5.1}$$

This function $F(\vec{d}, r)$, is minimized as an unconstrained function of $\vec{d}$, for a fixed value of r and the value of r is reduced sequentially. The sequence of minima so obtained converge to the constrained minimum of the problem as $r \to 0$.

5.3 UNCONSTRAINED MINIMIZATION

For unconstrained minimization, a number of well developed algorithms (e.g., Powell's Method, Davidon-Fletcher-Powell Method etc.) exist in the literature and are documented in standard text books on mathematical programming. Fox[19] has very rightly mentioned that picking a method is largely an art, although, to be sure, the better one's knowledge of the theory, the better he is at the art.

In the present work, the Davidon-Fletcher-Powell (DFP) method has been used for unconstrained minimization

and is discussed in the following section .

5.3.1 Davidon-Fletcher-Powell Method:

The Davidon-Fletcher-Powell (DFP) method[20, 21], also known as Variable Metric Method is a very powerful and well-used method. The algorithm for this method can be summarised as follows:

$$\vec{d}_{q+1} = \vec{d}_q + \alpha_q^* \vec{S}_q \tag{5.2}$$

where, $\vec{d}_q$ and $\vec{d}_{q+1}$ are the design vectors at the qth and (q+1)th iterations,

$\vec{S}_q$ is the move vector, and

α_q^* is the minimizing step length in $\vec{S}_q$ direction computed by linear minimization.

The move vector at any point $\vec{d}_q$ is obtained as

$$\vec{S}_q = - H_q \vec{G}_q \tag{5.3}$$

where, H_q is a positive definite symmetric matrix

and $\vec{G}_q = \nabla F(\vec{d}_q)$ (5.4)

is the gradient vector at $\vec{d}_q$

H_q is updated after every iteration using the formula

$$H_{q+1} = H_q + \alpha^*_q \frac{\vec{S}_q \, \vec{S}^T_q}{\vec{S}^T_q \, \vec{Q}_q} - \frac{(H_q \, \vec{Q}_q) \, (H_q \, \vec{Q}_q)^T}{\vec{Q}^T_q \, H_q \, \vec{Q}_q} \qquad (5.5)$$

in which $\vec{Q}_q = \vec{G}_{q+1} - \vec{G}_q$ (5.6)

to start with H_1 is taken to be the identity matrix.

5.4 LINEAR MINIMIZATION

For ill-behaved functions, of the type of penalty function which emerges in the minimum cost design of R.C. Silo, Golden Section Search Technique(22) is supposed to be the best. This method requires only function evaluations. The interval within which the minima is bracketed is successively reduced by ·618034 in this method. In one linear minimization ten internal reductions are performed which requires eleven function evaluations. The algorithm runs as follows:

Let $\vec{do}$ be the starting point and the linear minimization is to be performed along direction, $\vec{S}$, along which the minima is bracketed within an interval (Dist). The steps are:

1) Initialize K1 = 0, K2 = 0 and N = 0,

Take $R = 0.618034$

$\vec{d} = \vec{d}o$, and

Denote $Fo = F(\vec{d}o)$

2) Set $N = N + 1$

$\alpha_1 = R$ times Dist

$\alpha_2 = \text{Dist} - \alpha_1$

$\vec{d}_1 = \vec{d} + \alpha_1 \vec{S}$

and $\vec{d}_2 = \vec{d} + \alpha_2 \vec{S}$

3) If K_1 equals 1, go to step 4, otherwise continue.

Denote $F_1 = F(\vec{d}_1)$.

4) If K_2 equals 1, go to step 5, otherwise continue.

Denote $F_2 = F(\vec{d}_2)$.

5) If N equals 10, go to step 8, otherwise continue.

If F_1 is greater than F_2, go to step 6,

otherwise continue.

Set $\vec{d} = \vec{d}_2$

$F_2 = F_1$

$K_1 = 0$

$K_2 = 1$, go to step 7

6) Set $F_1 = F_2$

$K_1 = 1$

$K_2 = 0$

7) Set Dist $= \alpha_1$, go to step 2

8) Set F_{min} = Minimum of F_1 and F_2

If F_{min} equals F_1, go to step 9, otherwise continue.

$\alpha^* = (d2_i - do_i)/S_i$

9) $\alpha^* = (d1_i - do_i)/S_i$

The α^* is the desired minimizing step length.

5.5 GRADIENT EVALUATION

As the design-analysis cycle for the present silo problem uses some table, it is not possible to write expressions for gradient of the function F explicitly in terms of design variables. Finite difference scheme has been used to calculate the gradient. Backward difference and central difference schemes were tried and in both cases, the gradient values were approximately equal. However, in the present work, central difference scheme has been used.

For penalty function

$$F(\vec{d}, r) = f(\vec{d}) + r \sum_{j=1}^{m} \frac{1}{g_j(\vec{d})}$$

Pick Sd_i = minimum of $d_i/1000$ and 0.0001, and set

set $$\{\vec{d}1\} = \{\vec{d}\} - \begin{Bmatrix} 0 \\ 0 \\ sd_i \\ \cdot \\ \cdot \\ \cdot \\ 0 \end{Bmatrix}$$

and $$\{\vec{d}2\} = \{\vec{d}\} + \begin{Bmatrix} 0 \\ 0 \\ Sd_i \\ \cdot \\ \cdot \\ \cdot \\ 0 \end{Bmatrix}$$

Denote $f_1 = f(\vec{d}1)$, $f_2 = f(\vec{d}2)$

$g1_j = g_j(\vec{d}1)$ and $g2_j = g_j(\vec{d}2)$,

$j = 1, 2, \ldots\ldots m$

Then, $$G_i|_{\vec{d}} = \left[(f_2 - f_1) - r \sum_{j=1}^{m} \frac{g2_j - g1_j}{(g_j)^2}\right] / (2\, Sd_i) \qquad (5.7)$$

where, G_i is the ith component of $\nabla F(\vec{d})$,

$i = 1, 2, \ldots. n.$

CHAPTER VI

ILLUSTRATIVE EXAMPLE

6.1 DESIGN DATA

A 400 t capacity circular reinforced concrete silo with conical hopper bottom supported on six columns and used for the storage of wheat has been considered. The optimum design obtained through the computer programme developed in the present work, based on earlier discussions has been compared with the field design which has also been performed on the basis of I.S. Specifications and has been recently executed at Ashok Nagar (Madhya Pradesh - India). The data considered for the problem are as follows:-

The angle which hopper makes with the horizontal $(\alpha) = 45^{\circ}$

Diameter of outlet opening (D_{open}) = 30 cm

Clearance upto silo opening (V_{cl}) = 3.15 m

Effective length factor for column = 0.80

Since, the stored material is wheat, the following values have been used in numerical computations as suggested by I.S. Code[2]:

Unit weight of the sotred material (w) = 850 kg/m^3

Angle of internal friction for stored material (ϕ) = 28^o

Angle of wall friction in filling (ϕ'_f) = $\cdot75\phi$

Angle of wall friction in emptying (ϕ'_e) = $\cdot6\phi$

Pressure ratio in filling (λ_f) = 0.5

Pressure ratio in emptying (λ_e) = 1.0

Cost of concrete per cubic metre (C_c) = Rs. 150/-

Cost ratio for steel and concrete ($cost_r$) = 75

The additional cost of concrete for every metre increase in the constructional height above the the height for the fixed cost (P_{1c}) = 1 per cent

Height for fixed cost (H_{fc}) = 3 m

The IBM 7044-1401 computer at IIT Kanpur has been used. The results obtained have been presented in tabular and graphical form. The numerical experience and the behaviour of the problem have been discussed.

6.2 RESULTS AND DISCUSSIONS:

The optimum design of 400 t capacity R.C. Silo has been obtained first by starting from six different starting point and choosing:

is followed with the constant reduction factor in r. This ofcourse is at the expense of computer time. While the typical time taken (exclusive of compilation time) to arrive at the optimal design with varying reduction factor is around 4.25 minutes, it is only 3.1 minutes with constant reduction factor. Henceforth, only varying reduction factor to r as indicated above is used.

The results shown in Table 6.1 indicate the existence of local minima in the problem. Therefore, a set of another nine varyingly different starting points were considered and optimal designs were obtained. The results so obtained are given in Table 6.2. These results further established the existence of local minima in the problem. A plot of all the fifteen optimum design points obtained with varying reduction factor in the penalty parameter versus the optimum cost of silo structure is shown in Fig. 13. This plot is tending to be asymptotic to a total minimum cost of Rs. 27,000/ -. A comparision of the design variables corresponding to optimum design points having a total minimum cost of about Rs. 27,000/- does not show that the design is almost similar and from this it can be said with limited confidence that global minimum has not yet been obtained. At the optimum points, it is observed that the cost of

supporting structure i.e., column and ring-girder varies from 32 per cent to 41 per cent of the total cost while that of the super structure varies between 59 per cent to 68 per cent. The height to diameter ratio (H/D) varies between 2.7 to 5.0.

It is observed that constraint equations no. 37 and 38 are bounded at all the optimal designs. These represent respectively the lower bound on the hoop and vertical reinforcement in the vertical wall of the silo. The thickness of the vertical wall also tends to near minimum which is reflected from constraint equation no. 32. From this it can be concluded that the optimum design tends towards a silo diameter which results into near minimum wall thickness of the vertical wall with minimum reinforcement both in hoop and vertical directions. This is justified from the fact that with the decrease in the silo diameter, the pressure (both in the lateral and vertical direction) decreases at any point along the depth of the stored material (the variation of lateral pressure with depth for different diameters has been plotted in Fig. 14). With the decreased lateral pressure, the hoop force further decreases resulting into reduced thickness of wall as well as reduced hoop reinforcement. Furthermore, for a given capacity the decrease in diameter requires increase in height, and larger the

height of vertical wall more severe will be the stresses at the base of the wall due to lateral load, self weight of the wall and due to friction between the wall and the stored material. The optimal design, therefore, tries to tend to a diameter which results into minimum vertical reinforcement with near minimum thickness to resist the stresses in vertical wall. As such the optimum design is being governed by the lower bounds imposed on these variables. The other variables also adjust accordingly.

It has been observed that the cost of the silo structure is quite sensitive to silo-diameter and to the depth of ring-girder. A plot of these variables versus the total minimum cost for all the 15 design points obtained is shown in Figs. 15 and 16. These plots do not establish any easy mathematical correlation and only go to establish that the problem has a number of local minima.

The cost of a 400t capacity R.C. Silo field design executed at Ashok Nagar is Rs. 31813/-. The lowest cost optimum design obtained during the present work is Rs. 27123/-. This leads to a reduction of about 15 per cent in total cost of the material used. The field design and the lowest cost optimal design are shown in Table 6.3. However it may not be out of place

to mention here that all the optimum designs obtained in the present work have the total cost lower than the cost of the field design.

The IBM 7044-1401 computer takes about 5 minutes in the compilation of the programme. Additional 3 to $4\frac{1}{2}$ minutes are required for one complete run (i.e., starting from a starting point and reaching to a optimal point) depending upon the choice of the starting point.

6.3 CONCLUSIONS:

The programme developed in the present work is capable of improving the design of R.C. Silo. The automated optimum design as formulated in the present work has a number of local minima. Even with a numerical experimentation of fifteen design points it has not been possible to reach the global minimum. This obviously requires more intense search. However, a trend is observed that the optimum design tends towards a silo dimeter which results into near minimum wall thickness and the minimum hoop and vertical reinforcements in the silo wall as well as near minimum hopper thickness and reinforcements in it.

TABLE 6.1 OPTIMUM DESIGN WITH VARIOUS STARTING POINTS

(Showing Influence of Reduction in r also)

Particulars	units	Starting point (1)	Optimal Point CRF in r	Optimal Point VRF in r	Starting point (2)	Optimal Point CRF in r	Optimal Point VRF in r	Starting Point (3)	Optimal Point CRF in r	Optimal Point VRF in r
		1	2	3	1	2	3	1	2	3
D	m	5.00	4.942	5.151	4.700	4.749	5.056	5.200	4.857	5.042
T_w	m	0.165	0.164	0.166	0.165	0.159	0.165	0.165	0.155	0.161
T_h	m	0.165	0.157	0.163	0.165	0.164	0.160	0.165	0.155	0.162
H_r	m	1.300	1.258	1.261	1.000	1.046	0.964	1.500	1.474	1.491
B_r	m	0.800	0.640	0.538	0.800	0.673	0.634	0.800	0.539	0.502
D_{col}	m	0.700	0.597	0.603	0.700	0.603	0.610	0.700	0.596	0.591
A_{sw1}	P. of c/s	0.550	0.309	0.301	0.550	0.307	0.306	0.550	0.301	0.303
A_{sw2}	''	0.550	0.310	0.301	0.550	0.314	0.310	0.550	0.302	0.301
A_{sh1}	"	0.550	0.498	0.408	0.550	0.506	0.485	0.550	0.397	0.450
A_{sh2}	"	0.550	0.431	0.560	0.550	0.465	0.490	0.550	0.368	0.558
A_{sr1}	"	1.000	1.262	1.085	1.000	1.058	0.996	1.000	1.205	0.890
A_{sr2}	"	1.000	1.046	1.057	1.000	1.083	1.104	1.000	1.071	1.059
A_{sr3}	"	1.900	1.807	1.758	1.900	2.033	1.918	1.900	1.976	2.030
A_{scs}	"	0.550	0.725	0.452	0.550	0.509	0.55[illegible]	0.550	0.439	0.527
A_{scl}	"	2.200	2.205	2.252	2.200	2.528	2.325	2.200	2.346	2.303
H_c	m	4.200	4.213	4.314	4.350	4.329	4.564	4.100	3.955	4.030
H_{vw}	m	23.798	24.364	22.407	26.966	26.403	23.269	21.983	25.234	23.403
H/D	m/m	4.760	4.930	4.350	5.737	5.559	4.602	4.228	5.195	4.642
$(Cost)_T$	Rs.	35964	28986	27123	34774	28224	27216	37042	27737	27396
$(Cost)_S$	P. of C_T	58.200	60.8	62.900	66.0	63.1	63.8	55.9	60.2	61.0
$(Cost)_{SUPP}$	"	41.800	39.2	37.1	34.0	36.9	36.2	41.1	39.8	39.0
Bounded constraints			30,32,33, 37,38,39, 40	30,32,33, 37,38,39, 44		30,32,33, 37,38,39, 40,44	30,32,33, 37,38,39, 40		30,32, 33,38, 39,40, 44	30,32, 33,37, 38,39

Particular	Units	For St. Pt. 4: 1	2	3	For St Pt 5: 1	2	3	For St. Pt. 6: 1	2	3
D	m	5.0	4.942	5.102	4.7	4.729	4.908	5.300	4.998	5.195
T_w	m	0.165	0.166	0.167	0.165	0.159	0.161	0.165	0.163	0.170
T_h	m	0.165	0.161	0.155	0.165	0.158	0.158	0.165	0.154	0.163
H_r	m	1.500	1.461	1.515	1.500	1.477	1.509	1.500	1.481	1.490
B_r	m	0.800	0.590	0.494	0.800	0.566	0.552	0.800	0.537	0.547
D_{col}	m	0.700	0.596	0.592	0.700	0.594	0.596	0.700	0.594	0.587
A_{sw1}	P.of c/s	0.550	0.307	0.301	0.550	0.310	0.307	0.550	0.322	0.304
A_{sw2}	"	0.550	0.304	0.310	0.550	0.300	0.336	0.550	0.304	0.311
A_{sh1}	"	0.550	0.453	0.511	0.550	0.420	0.460	0.550	0.403	0.515
A_{sh2}	"	0.550	0.408	0.532	0.550	0.434	0.441	0.550	0.624	0.525
A_{sr1}	"	1.000	0.830	0.758	1.000	0.884	0.999	1.000	1.235	1.140
A_{sr2}	"	1.000	1.234	1.108	1.000	1.062	1.051	1.000	0.891	0.850
A_{sr3}	"	1.900	1.998	1.964	1.900	2.095	1.823	1.900	1.969	1.879
A_{scs}	"	0.550	0.517	0.722	0.550	0.621	0.492	0.550	0.826	0.603
A_{scl}	"	2.200	2.247	2.117	2.200	2.342	2.258	2.200	2.020	2.349
H_c	m	4.000	4.011	4.036	3.850	3.887	3.945	4.150	4.018	4.107
H_{vw}	m	23.798	24.363	22.846	26.966	26.638	24.712	21.152	23.814	22.023
H/D	m/m	4.760	4.929	4.478	5.737	5.633	5.035	3.991	4.764	4.239
$(Cost)_T$	Rs.	37281	29204	27720	37846	28700	28387	36957	28435	28717
$(Cost)_S$	P. of C_T	57.7	60.5	67.6	60.5	62.0	62.0	55.0	61.0	60.7
$(Cost)_{SUPP}$	"	42.3	39.5	37.4	39.5	38.0	38.0	45.0	39.0	39.3
Bounded Constraints			30,32,33 37,38,39 40,44	30,33,37 37,38,39		30,32,33 37,38,39 40,43	30,32,33 37,38,39 40,44		30,32,33 37,38,39	30,33,37 38,39,40

TABLE 6.2 OPTIMUM DESIGN WITH VARIOUS STARTING POINTS

Particulars	Units	Starting Point	Opt. Pt.	St. Pt.	Opt. Pt.	St. Pt.	Opt. Pt.	St. Pt.	Opt. Pt.
		1		2		3		4	
D	m	5.500	5.315	4.500	4.959	5.300	5.228	4.000	5.136
T_w	m	0.165	0.171	0.165	0.165	0.175	0.170	0.165	0.173
T_h	m	0.165	0.160	0.165	0.157	0.190	0.189	0.165	0.156
H_r	m	1.500	1.469	1.200	1.177	1.000	1.025	1.500	1.418
B_r	m	0.800	0.465	0.800	0.579	0.750	0.527	0.800	0.496
D_{col}	m	0.700	0.597	0.700	0.604	0.600	0.630	0.700	0.597
A_{sw1}	P.of c/s	0.550	0.309	0.550	0.314	0.600	0.316	0.550	0.355
A_{sw2}	"	0.550	0.335	0.550	0.306	0.580	0.333	0.550	0.518
A_{sh1}	"	0.550	0.447	0.550	0.500	0.600	0.521	0.550	0.564
A_{sh2}	"	0.550	0.350	0.550	0.405	0.600	0.525	0.550	0.551
A_{sr1}	"	1.000	1.195	1.000	0.981	1.400	1.444	1.000	0.789
A_{sr2}	"	1.000	0.745	1.000	1.163	1.800	1.861	1.000	1.003
A_{sr3}	"	1.900	2.023	1.900	1.823	2.100	2.039	1.900	1.908
A_{scs}	"	0.550	0.488	0.550	0.480	0.600	0.588	0.550	0.566
A_{scl}	"	2.200	2.250	2.200	2.323	1.900	1.982	2.2	2.214
H_c	m	4.250	4.189	4.050	4.303	4.650	4.589	3.500	4.150
H_{vw}	m	19.622	21.032	29.437	24.193	21.152	21.745	37.314	22.542
H/D	m/m	3.568	3.957	6.542	4.878	3.991	4.159	9.328	4.389
Total Cost C_T	Rs.	36852	27506	36636	27606	37440	28481	40501	29906
Sup. Cost	P.of C_T	53.4	62.7	66.2	63.6	59.8	62.4	67.8	67.0
Supp. Str. Cost	"	46.6	37.3	33.8	36.4	40.2	37.6	32.2	33.0
Bounded Constraints			30,33,35 37,38,39 40,44		30,32,33 37,38,39 40,44		30,37,38 39,40		30,33,37,38

Continued next page.

Contd. Table 6.2

Particulars	Units	St.Pt. 5	Opt.Pt.	St.Pt. 6	Opt.Pt.	St.Pt. 7	Opt.Pt	St.Pt. 8	Opt.Pt	St. Pt. 9	Opt. Pt.
D	m	6.00	5.688	7.00	6.049	6.400	5.815	5.700	5.501	6.000	5.602
T_w	m	0.180	0.184	0.200	0.187	0.191	0.185	0.180	0.179	0.180	0.181
T_h	m	0.220	0.219	0.230	0.226	0.210	0.210	0.195	0.194	0.195	0.194
H_r	m	1.400	1.440	1.500	1.545	1-350	1.393	1.000	0.985	1.000	1.004
B_r	m	0.700	0.408	0.700	0.386	0.500	0.392	0.850	0.624	0.850	0.624
D_{col}	m	0.750	0.652	0.800	0.666	0.700	0.649	0.700	0.628	0.700	0.627
A_{sw1}	P. of c/s	0.750	0.482	0.800	0.328	0.600	0.435	0.700	0.463	0.700	0.472
A_{sw2}	"	0.600	0.336	0.600	0.315	0.600	0.432	0.600	0.363	0.600	0.371
A_{sh1}	"	0.750	0.714	0.750	0.639	0.580	0.576	0.600	0.577	0.600	0.577
A_{sh2}	"	1.300	1.258	1.400	1.280	1.000	0.992	0.600	0.581	0.600	0.581
A_{sr1}	"	1.400	1.366	1.500	1.493	1.500	1.466	1.500	1.461	1.500	1.463
A_{sr2}	"	1.500	1.481	1.500	1.450	1.500	1.455	2.000	1.957	2.000	1.958
A_{sr3}	"	1.400	1.414	1.300	1.484	1.900	1.846	1.800	1.764	1.800	1.766
A_{scs}	"	0.800	0.755	0.600	0.583	0.800	0.762	0.800	0.763	0.800	0.763
A_{scl}	"	2.00	2.111	2.500	2.679	1.800	1.960	1.600	1.931	1.600	1.946
H_c	m	4.600	4.404	5.000	4.479	4.850	4.515	4.850	4.765	5.00	4.797
H_{vw}	m	16.441	18.328	11.992	16.170	14.412	17.524	18.250	19.613	16.441	18.906
H/D	m/m	2.740	3.222	1.713	2.673	2.252	3.014	3.202	3.565	2.740	3.375
Total Cost C_T	Rs.	40371	30733	46648	31006	36506	31176	39095	30497	38946	31857
Sup. Cost	P.of C_T	55.7	64.1	51.1	59.6	59.4	64.0	57.6	61.5	55.6	60.7
Supp.Str. Cost	"	44.3	35.9	48.9	40.4	40.6	36.0	42.4	38.5	44.4	39.3
Bounded Constraints			15,19,30 35,37,38	15,19,35 37,38	15,19,35 37,38		15,27,30 35,37,38		30,37,38		30.37 38

TABLE 6.3 FIELD DESIGN AND OPTIMUM DESIGN

Particulars	Units	Field Design*	Minm. of opt. Design**
D	m	7.000	5.151
T_w	m	0.175	0.166
T_h	m	0.250	0.163
H_r	m	1.500	1.261
B_r	m	0.500	0.538
D_{col}	m	0.5642	0.603
A_{sw1}	P. of c/s	0.865	0.301
A_{sw2}	''	0.301	0.301
A_{sh1}	''	0.805	0.408
A_{sh2}	''	1.424	0.560
A_{sr1}	''	0.400	1.085
A_{sr2}	''	0.600	1.057
A_{sr3}	''	1.000	1.785
A_{scs}	''	0.463	0.452
A_{scl}	''	3.700	2.252
H_c	m	5.000	4.314
H_{vw}	m	11.992	22.407
H/D	m/m	1.713	4.350
Total Cost C_T	Rs.	31813	27123
Sup. Cost	P. of C_T	65	62.9
Supp. Str. Cost	P. of C_T	35	37.1
Bounded Constraints		18,19,30,38, 41, 45	30,32,33,37,38, 39, 44

* Modified field design

** Giving minimum cost out of all the 15 optimum designs.

6.4 SCOPE FOR FUTURE WORK:

The silo structure can be considered as a shell of revolution and rigorous analysis of the shell under the loads can be embedded in the programme of automated optimum design.

The formulation of the problem given in the present work can be slightly modified by specifying all those design variables which are tending to near minimum values as pre-determined design parameters at these minimum values (e.g., the reinforcements in silo wall and hopper bottom). This will reduce the size of the problem in the design space and thus may improve the nature of the function to enable us to reach the global minimum.

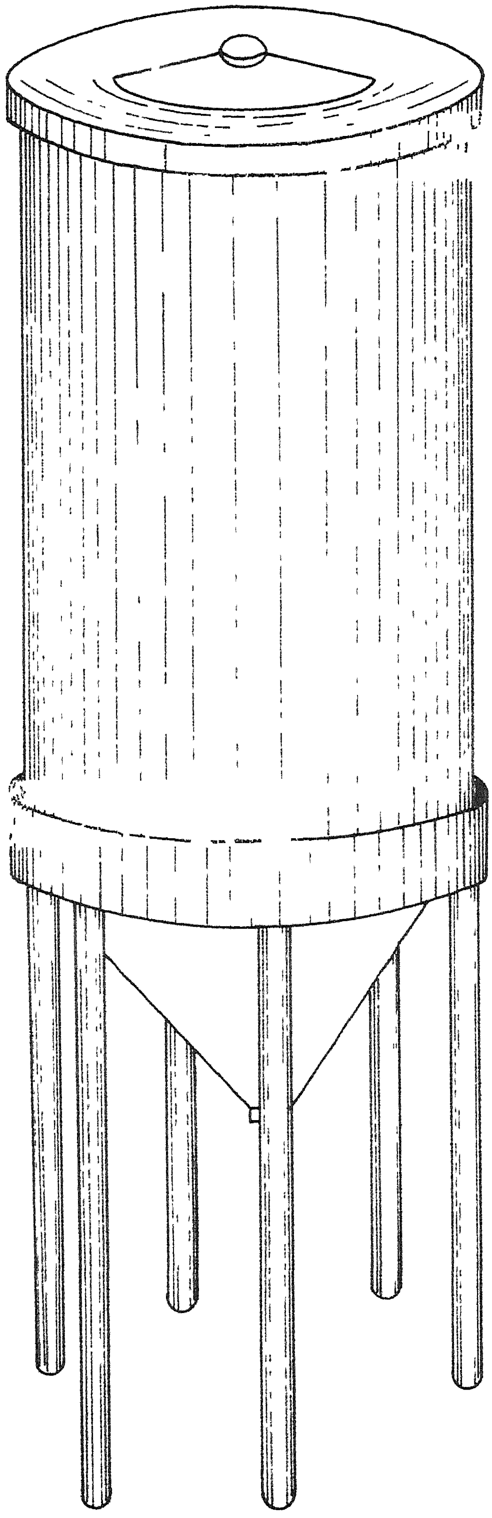
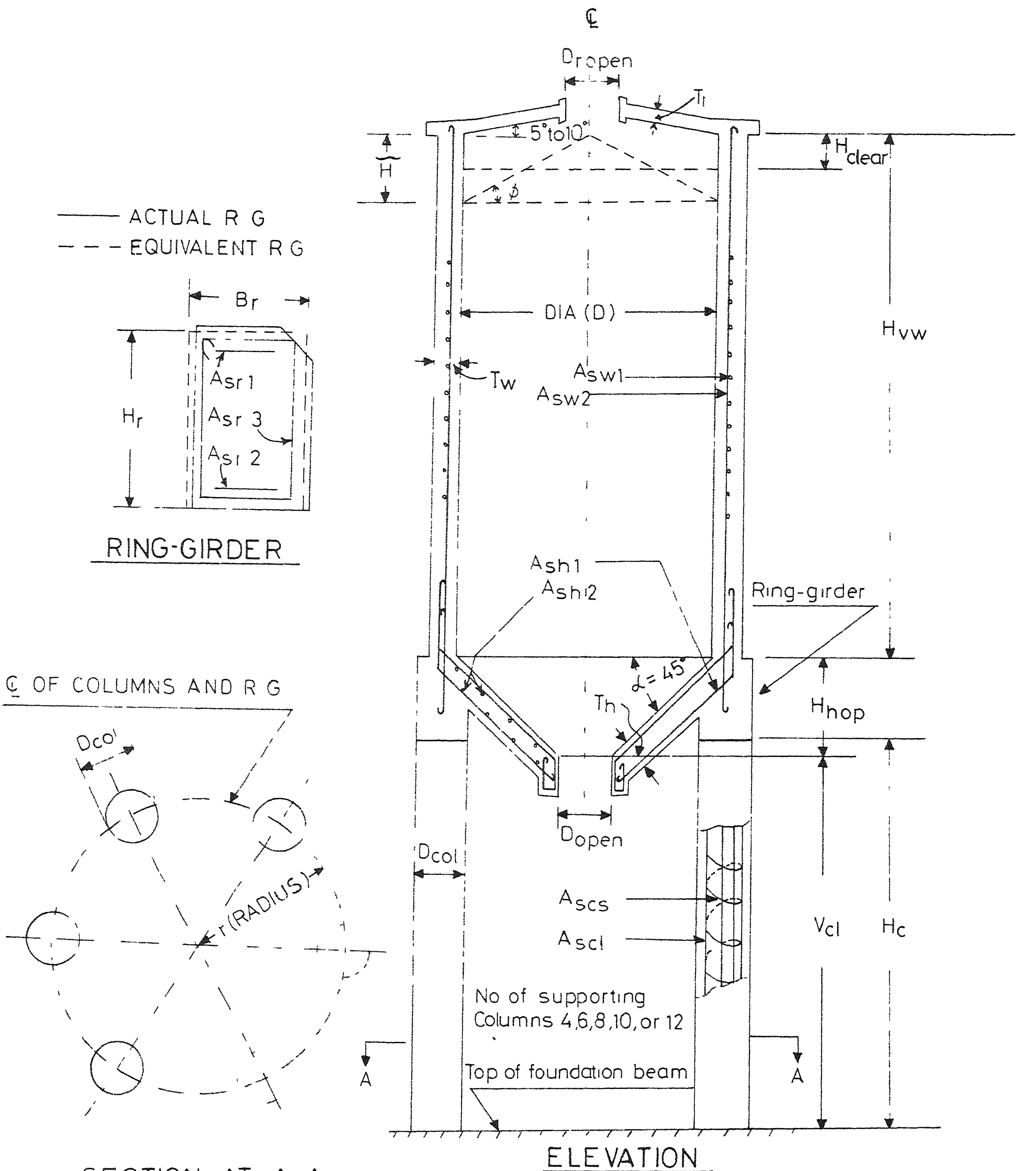


FIG 1 A VIEW OF THE PROPOSED SILO



Note
1. $\bar{H}$ is twice of H_{clear}
2. Ring girder reinforcements correspond to equivalent C/S
3. Columns are equally spaced

FIG 2 SILO DETAILS

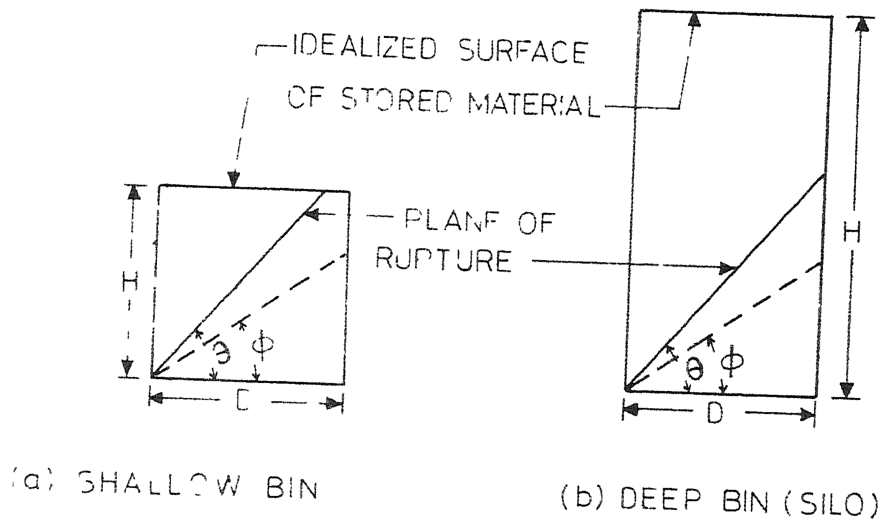


FIG 3 PLANE OF RUPTURE IN SHALLOW AND DEEP BINS

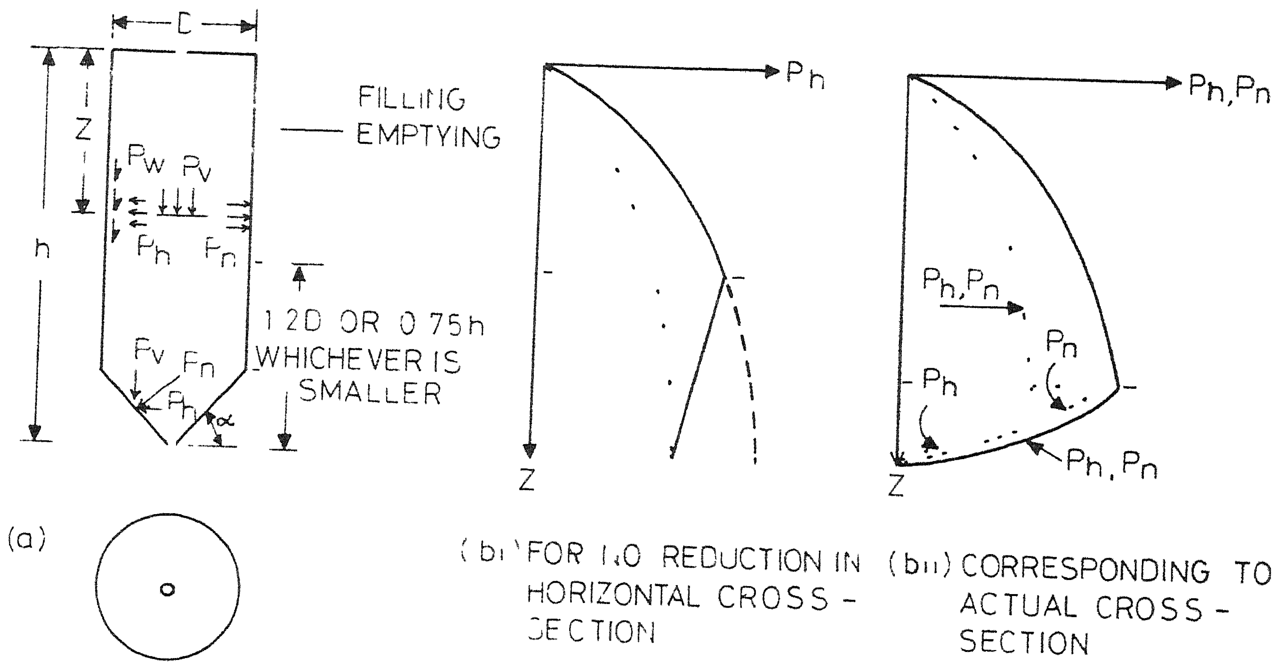
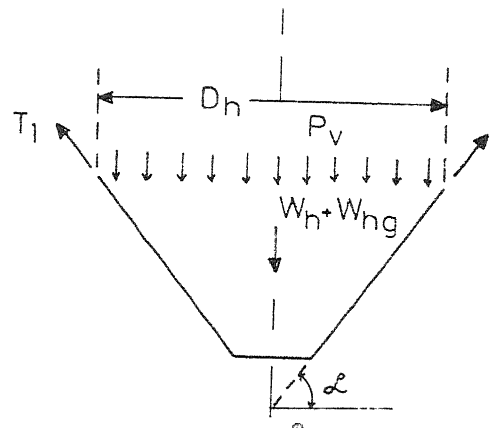
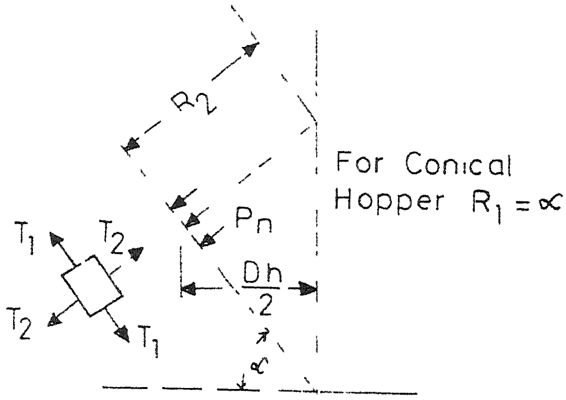


FIG 4 (a) PRESSURES IN SILO AND (b) THEIR VARIATION WITH DEPTH



(a) FOR MERIDINAL FORCE



(b) FOR RING OR HOOP FORCE

FIG 5 EQUILIBRIUM CONSIDERATION IN HOOPER BOTTOM

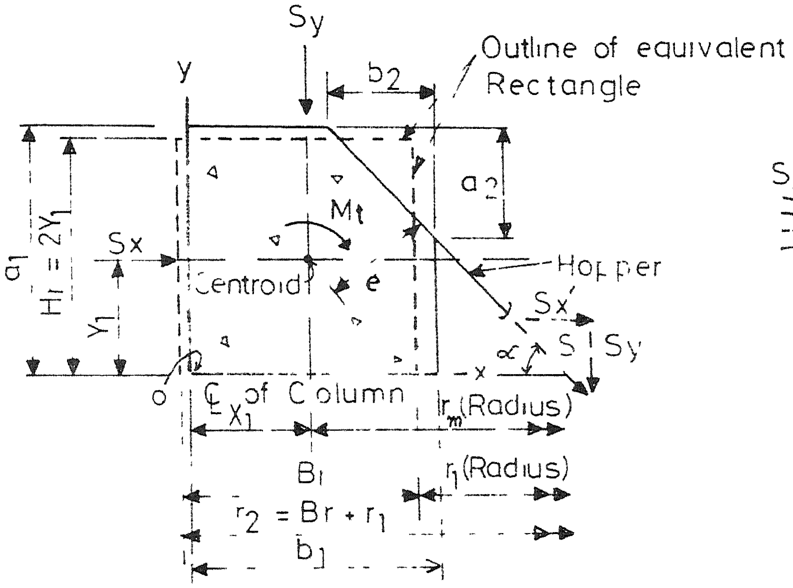
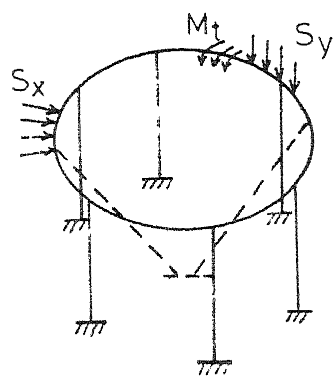
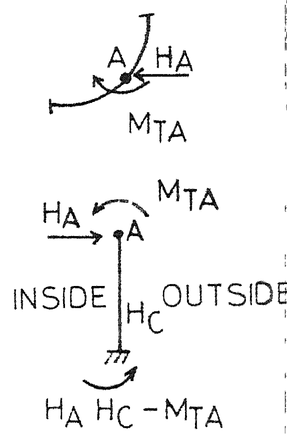


FIG 6 RING GIRDER CROSS-SECTION



(a) BASIC FRAME



(b) FREE BODY

FIG 7 FORCE SYSTEM ACTING ON RING-GIRDER AND COLUMN

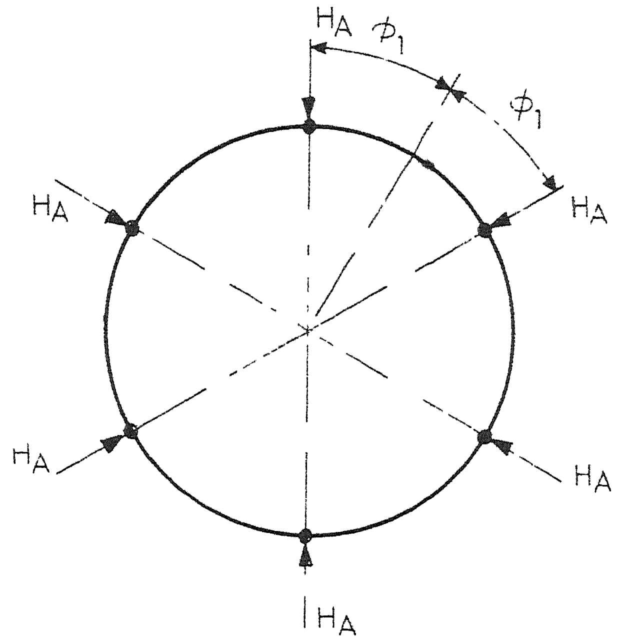


FIG 8 LATERAL FORCES APPLIED TO RING-GIRDER FROM COLUMNS

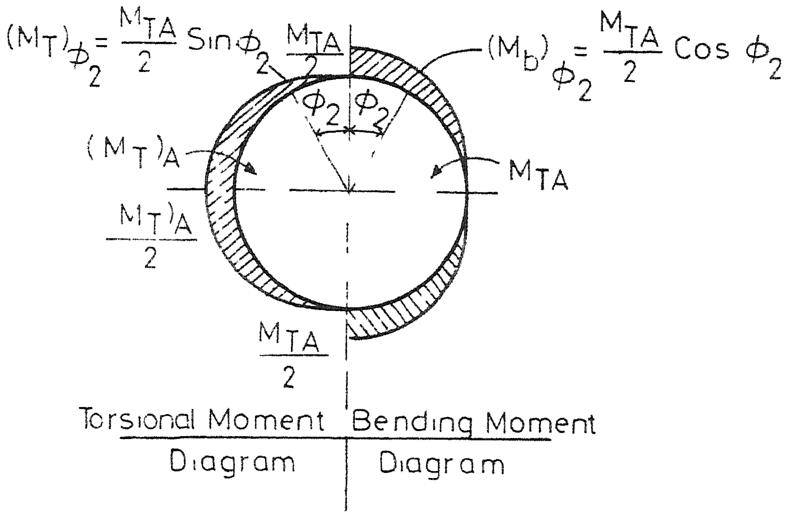


FIG 9 MOMENT DIAGRAMS DUE TO DIAGONAL OPPOSITE EQUAL CONCENTRATED MOMENTS

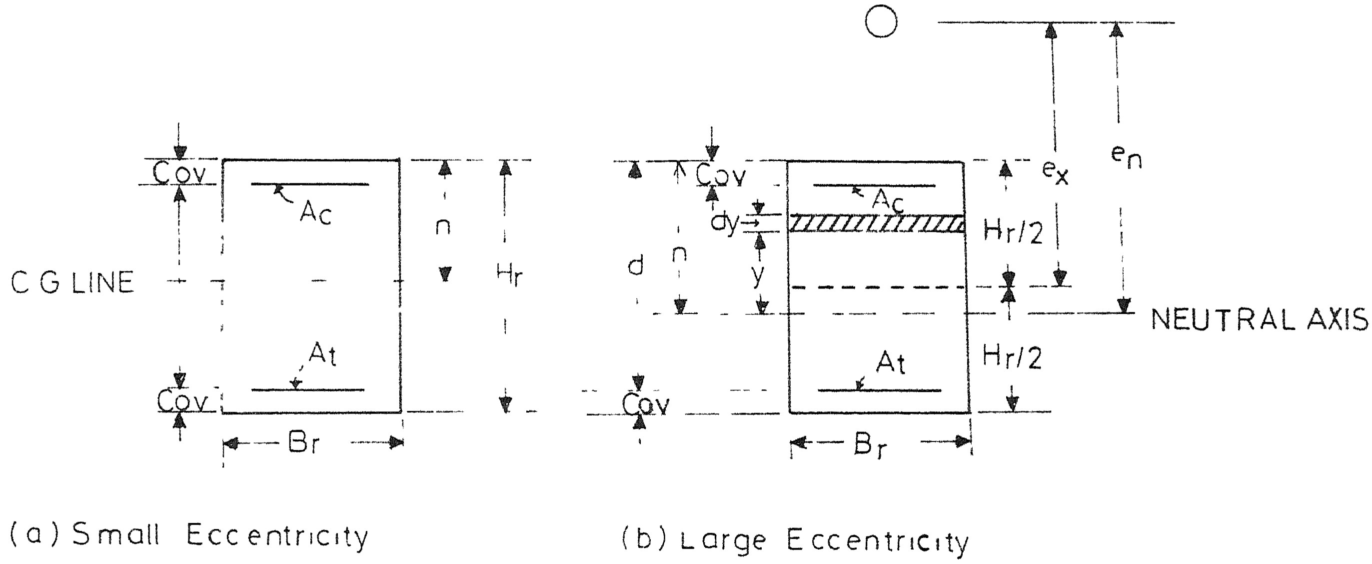


FIG 10 GIRDER CROSS-SECTION UNDER ECCENTRIC LOADING

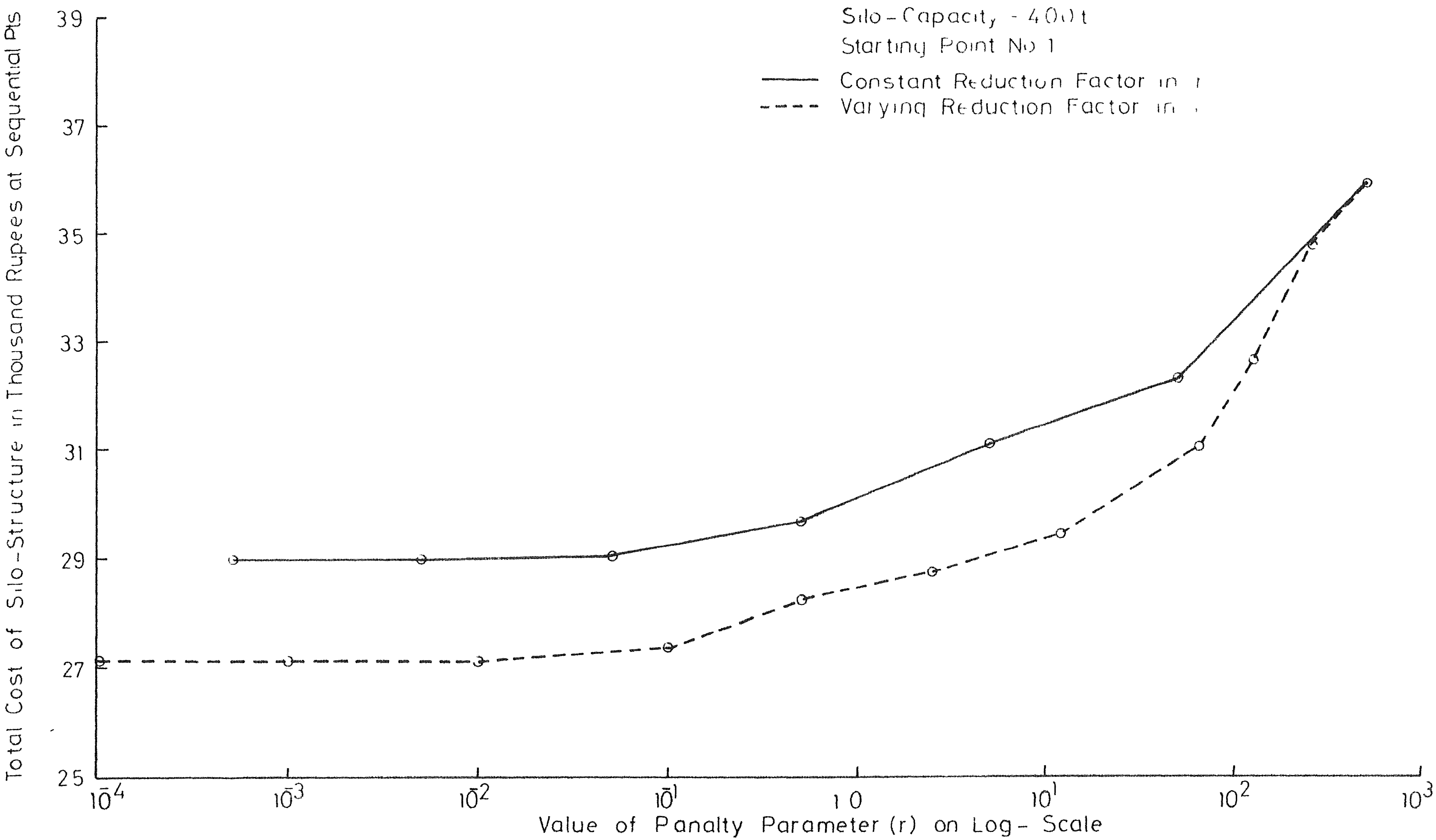


FIG 11 INFLUENCE OF PENALTY PARAMETER OVER COST

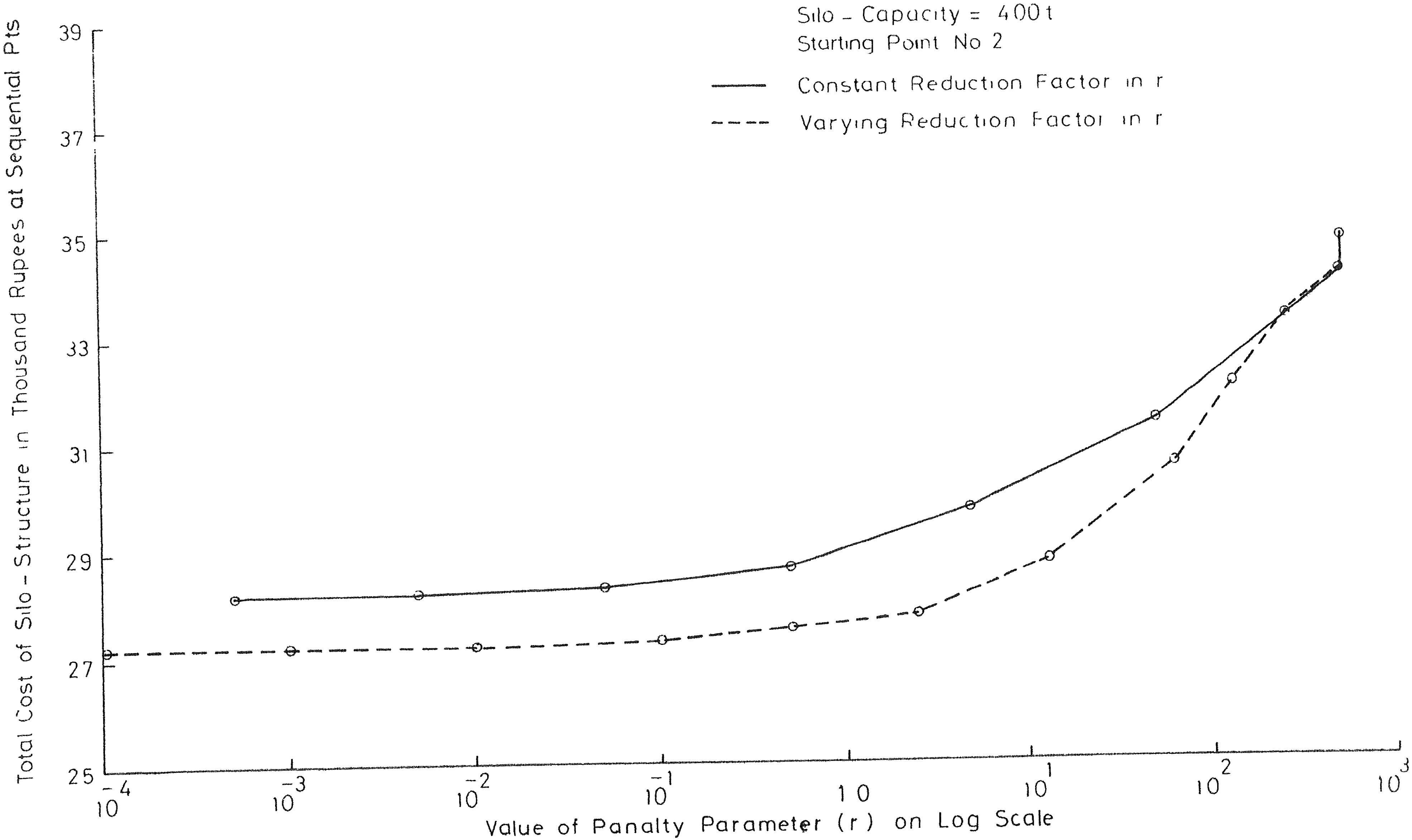


FIG 12 INFLUENCE OF PENALTY PARAMETER OVER COST

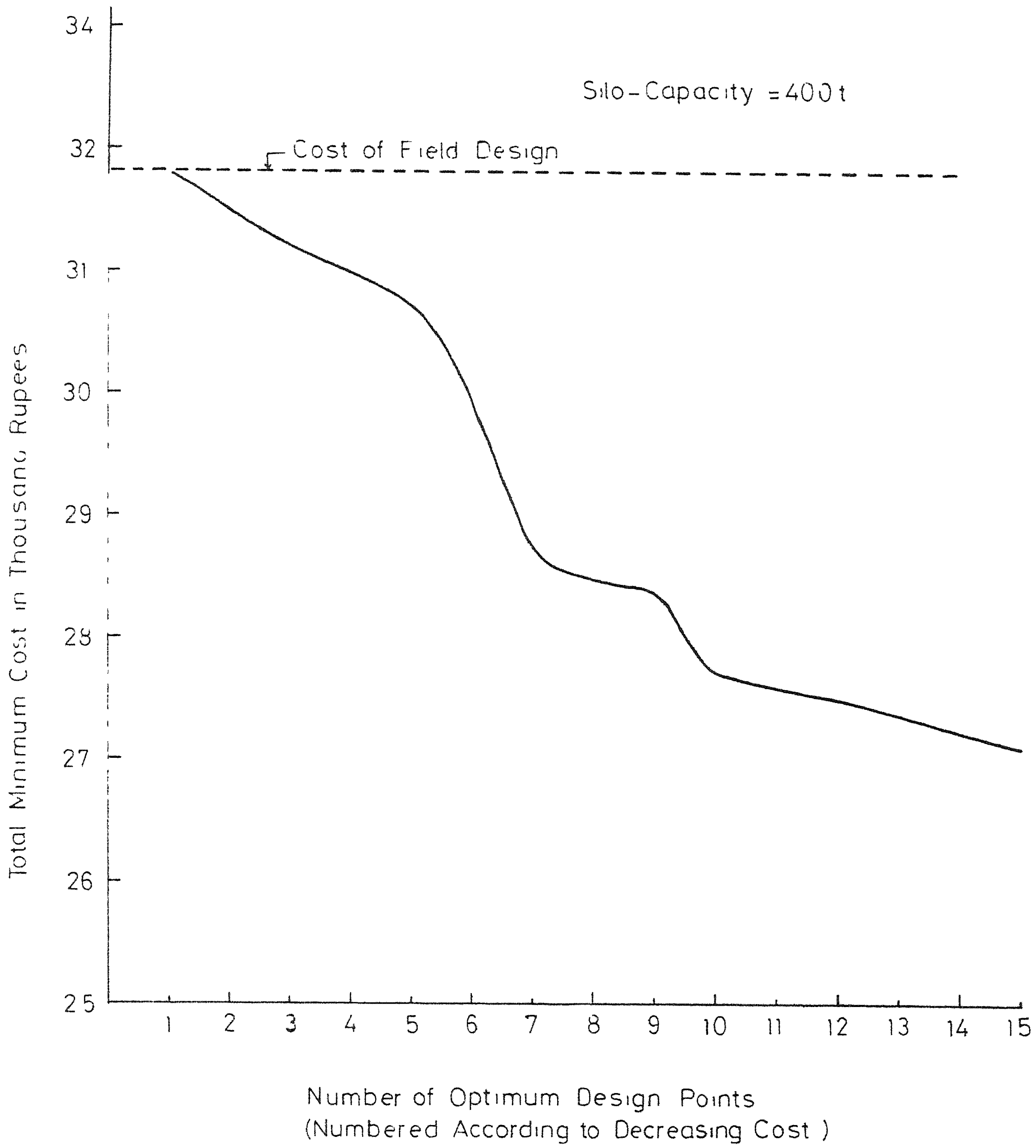


FIG 13 TOTAL MINIMUM COST VERSUS NUMBER OF OPTIMUM DESIGN POINTS

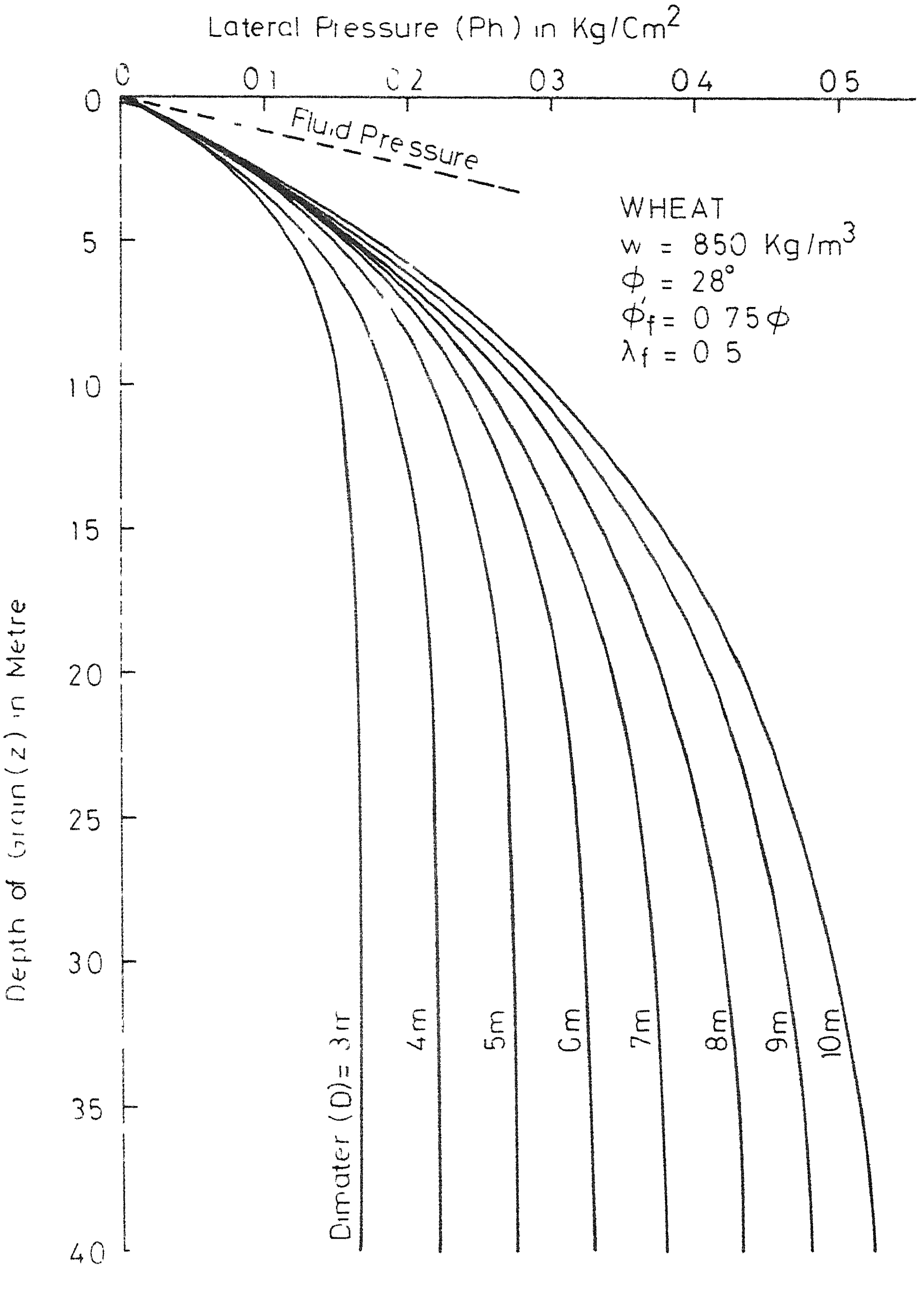


FIG 14 LATERAL PRESSURE IN SILO AS PER I S SPECIFICATION(2)

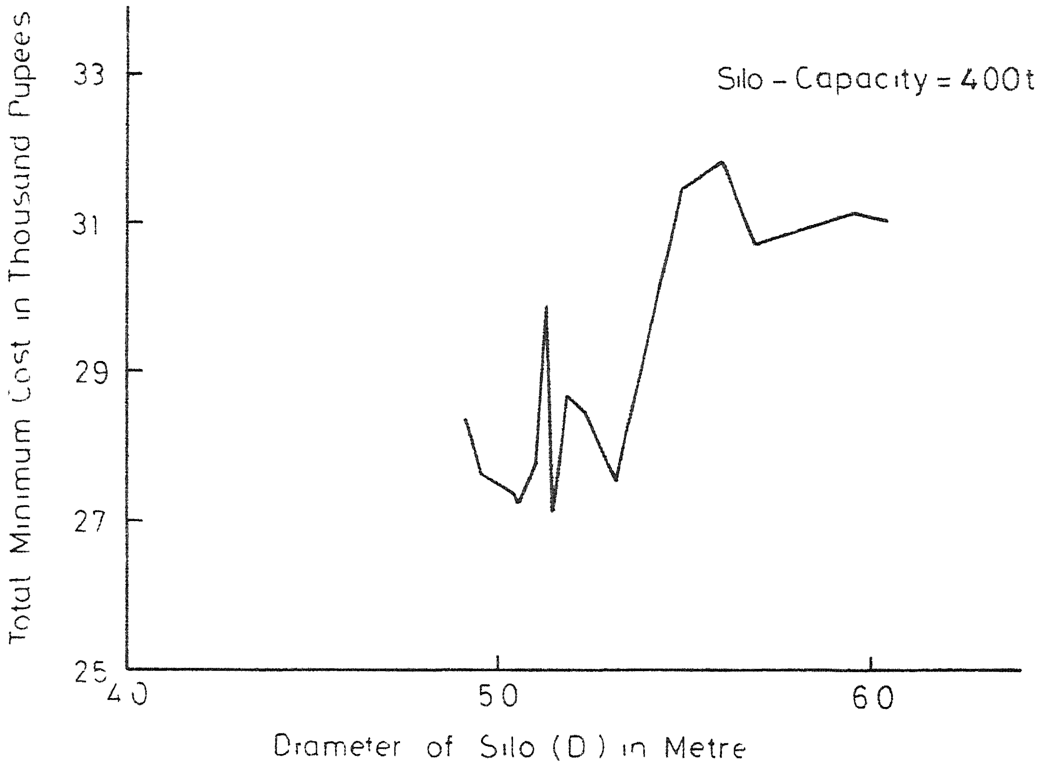


FIG 15 TOTAL MINIMUM COST VERSUS SILO-DIAMETER

FIG 16 TOTAL MINIMUM COST VERSUS GIRDER-DEPTH

LIST OF REFERENCES

1. ... Bins and Silos for Storage of Grains, The Concrete Association of India, Cement House, Queen's Road, Bombay-1, 1958.

2. ... I.S. 4995-1968, Criteria for Design of Reinforced Concrete Bins (Silos) for Bulk Food Grains Storage, Indian Standards Institution, Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Delhi-1.

3. ... National Building Code of India - 1970, Indian Standards Institution, Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Delhi-1.

4. JANSSEN, H.A., Experiments on grain pressures in Silos (Versuche uber getreiderdruck in Silozellen), Zeitschrift des Vereines Deutscher Ingenieure, August 1885, v.39, pp. 1045-1042, (in German).

5. AIRRY, W., The pressure of Grain. Minutes of Proceedings, Institution of Civil Engineers, London, v. 131, 1897, pp. 347-358.

6. REIMERT, M. and REIMBERT, A., Silos - Theoretical and Practical Treatise (Silos-Traite Theorique et Pratique), Editions Eyrolles, Paris, 1956 (in French).

7. WALKER, D.M., An Approximate Theory for Pressure and Arching in Hoppers, Chemical Engineering Science, v. 21, 1966, pp. 975-997.

8. JENIKE, A.W. and JOHANSON, J.R., Bin Loads, J. of the Structural Division, April 1968, ST4, Proc. of the ASCE, v. 94, pp. 1012-1041.

9. THIEMER, O.F., Failures of Reinforced Concrete Grain Silos, Publication 68-MH-36, ASME, N.Y. 1968 (Condensed in J. of Engineering for Industries, Trans. ASME, v. 91 (B2), May 1969, pp. 406-413).

10. SAFARIAN, S.S., Design Pressures of Granular Materials in Silos, J. of the American Concrete Institute, August 1969, v. 66, pp. 647-655.

11. ... Design Loads for Building: Loads in Silos, German Standard DIN 1055, Blatt 6, Berlin, Nov. 1964(in German).

12. ... Instructions for Design of Silos for Granular Materials (ukazania po proectirovaniu silosov dlia siputshich materialov), Soviet Code CH-302-65. Gosstroy, USSR, Moscow, 1965 (in Russian).

13. ... Bin Wall Design and Construction, Report by ACI Committee 313, J. of the American Concrete Institute, July 1968, v. 65, pp. 499-506.

14. ... KETCHUM, M.S., Design of Walls, Bins and Grain Elevators, Mc-Graw Hill Book Co. Inc., New York, 1909 (and 3rd ed. 1919).

15. ... Bunkers and Silos for Industrial Purposes, The Concrete Association of India, Cement House, 121, Queens Road, Bombay-1. 1958.

16. SAFARIAN, S.S. and HARRIS, E.C., Determination of Minimum Wall Thickness and Temperature Steel in Conventionally Reinforced Concrete Silos, J. of the American Concrete Institute, July 1970, v. 67, pp. 539-547.

17. SAFARIAN, S.S., Design of a Concrete Ring Beam and Column System Supporting a Silo Hopper, J. of the American Concrete Institute, Oct. 1969, v. 66, pp. 103-110.

18. FIACCO, A.V. and Mc CORMICK, G.P., Non-linear Programming - Sequential Unconstrained Minimization Technique, Wiley, New York, 1968.

19. FOX, R.L., Optimization Methods for Engineering Design, Addison-Wesley Publishing Co. 1971.

20. DAVIDON, W.C., Variable Metric Method for Minimization, Argonne National Laboratory, Report No. ANL 5990, 1959.

21. FLETCHER, R. and POWELL, M.J.D., A Rapidly Convergent Descent Method for Minimization, Computer Journal, v. 6, 1963, pp. 163-168.

22. COXETER, H.S.M., Golden Section, Scripta Mathematician, 1954.

APPENDIX

COMPUTER PROGRAMME

The programme for the present work was written for IBM 7044 Computer in Fortran IV language. The complete programme consists of:

(A) a main programme named INPUT which reads the input data, generates the normalized variables, goes to unconstrained minimization routine, reduces the value of penalty parameter, checks the convergence and prints the output, and

(B) the other eight subroutines namely:

i) DFPOWL which provides the general working of the DFP method and is called from INPUT,

ii) GRAD which calculates the gradient as per central difference scheme and is called from DFPOWL,

iii) HASM which updates the Hassian Matrix and is called from DFPOWL,

iv) GOLDEN which performs the linear minimization as per Golden Section Search Technique and is called from DFPOWL,

iv) PENAL which converts the normalized variables to the actual variables, goes to the analysis-design subroutine, calculates the constraints related with upper and lower limits on the

design variables and finally gives the penalty function value,

vi) ANLSIS which calculates the cost of the silo structure and all the constraints other than those related with upper and lower bounds on design variables and is called from PENAL,

vii) SPECTR which gives the average acceleration as per I.S. Specification[3] and is called from the ANLSIS, and

viii) TORSON which gives the torsional properties for a rectangular cross-section as per Table 3.2 and is also called from ANLSIS.

The complete listing of these sub-routines are as follows:

C.G160 FORTRAN SOURCE LIST

ISN SOURCE STATEMENT

```
$IBFTC INPUT
CC
C          AUTOMATED  OPTIMAL  DESIGN  OF
C                REINFORCED  CONCRETE
C                     SILO
C
      DIMENSION D(15),DN(15),DMIN(15),SPAN(15),GD(45)
      DATA N,NC,NCN/15,45,30/
      DATA EPS1,EPS2/0.0001,0.0000001/
      DATA DMIN/1.0,2*0.15,2*0.3,0.4,8*0.003,0.008/
      DATA SPAN/8.0,2*.15,2*1.5,0.8,8*0.02,0.032 /
      DATA GCONCM,SIGCB,SIGC,SIGTB,SIGT,SIGS,SIGBON,SIGBR/
     1200.0,70.0,50.0,17.0,12.0,17.0,8.0,40.0 /
      DATA FS,FSH,FS1,FS2  /1300.0,1000.0,1000.0,1250.0 /
      DATA ES / 2.1E+06/
      DATA W,FI,WC,DOPEN,TTA / 850.0,28.0,2400.0,0.3,45.0 /
      DATA WSEPF,WINDPR,ESEPF,SISCO3,FZ3,WBETA/0.7,150.,1.5,.04,.3,1.0/
      DATA BCOV,CCOV,ELFACT,VCLEAR/0.04,0.04,0.8,3.15/
      DATA WTOP,TMT,CRATIO,TTARUF,THR,ROPEN/100.,.0,75.,5.,.08,.3 /
      DATA CC / 35.0 /
      PI=4.0*ATAN(1.0)
      CALL FLUN(10000)
      AMODR=2800.0/GCONCM
      IF(AMODR.GT.18.0)AMODR=18.0
      AMODR1=AMODR-1.0
      EC=ES/AMODR
      FI=FI*PI/180.0
      TTA=TTA*PI/180.0
      TTARUF=TTARUF*PI/180.0
      AMU=TAN(FI)
      FIF=0.75*FI
      FIE=0.6*FI
      AMUF=TAN(FIF)
      AMUE=TAN(FIE)
      ALDAF=0.5
      ALDAE=1.0
      COMMON /NMBER/ NFE,NGE,NGS,NMA
      COMMON /PROB/NC,NCN
      COMMON /NORML/ DMIN,SPAN
      COMMON /CONCR/GCONCM,SIGCB,SIGC,SIGTB,SIGT,SIGS,SIGBON,SIGBR,AMODR
      COMMON /STEEL/ FS,FSH,FS1,FS2,ES,EC,AMODR1,PI
      COMMON /COST/FONEW,CC,CR,CAP,WTOP,TMT,W,WC,FI,DOPEN,TTA,AMUF,AMUE,
     *ALDAF,ALDAE,COSTS,CCSTC,COSTR,CRATIO,TTARUF,THR,ROPEN
      COMMON/DTFT/BCOV,CCOV,ELFACT,VCLEAR,WSEPF,WINDPR,ESEPF,SISCO3,FZ3
     * ,WBETA
      COMMON /SHAPE/ H,HC
  111 CONTINUE
      PRINT 11
      CALL TIME(M)
      NFE=0
      READ2,CAP,(D(I),I=1,N)
      PRINT1,CAP,(D(I),I=1,N)
    1 FORMAT(* OPT.COST DESIGN OF FOOD GRAIN STORAGE SILO*,5(3H **),/1X,
     *42(1H-),///* CAPACITY=*,F10.5,* TONNES*,//* VARIABLES ARE . .*,/*
     * (1)DIA.AND (2) THICKNESS OF SILO CYLINDER,(3) THICKNESS OF SILO
```

```
 ISN         SOURCE STATEMENT

            *HOPPER,(4) HEIGHT AND (5) WIDTH OF RING GIRDER*,/* (6) DIA.OF SUPP
            *ORTING COL.AND PER.REINF.AS (7) HOOP AND (8) VERTICAL REINF+FOR V.
            * WALL*,/* (9) MERIDINAL AND (10) CIRCULAR REINF.FOR HOPPR.(11)UP.
            *AND (12) LOWER LONG.AND (13) STIRP REINF.FOR R.G.*,/* (14) SPIRAL
            * AND (15) LONG.REINF.FOR COL..*,/1X,8F10.5,/1X,8F10.5)
  67   2     FORMAT(8F10.5)
  70   3     FORMAT(* CONSTRANTS ARE*,/10(6E16.7,/))
  71   4     FORMAT(* STARTING POINT IN INFEASIBLE DOMAIN*)
  72   5     FORMAT(/* COST T=*,E15.7,* R=*,E15.7,* FUNC.V.=*,E15.7,*COST OF SU
            *P.S,COL,R.G.*,3E13.5)
  73   6     FORMAT(/50X,*NUMBER OF FUNC.EVAL.*,I5,/50X,*NUMBER OF GRAD.EVAL.*,
            *I5,/50X,*NUMBER OF GOLDEN SER*,I5,/50X,*NUMBER OF MATRIX ASS*,I5/)
  74   7     FORMAT(* COST IMP.IN LAST ITER.*,E15.7,/* PENAL PART*,E15.7,/
            ** TOTAL,SUP.S.,SUP.C.,R.G.COSTS ARE*,4E13.5)
  75   8     FORMAT(* ERR2=*,E15.7,* . GOING FOR NEXT CY.WITH R=*,E15.7)
  76   9     FORMAT(* ERR1=*,E15.7,* . GOING FOR NEXT CY.WITH R=*,E15.7)
  77  10     FORMAT(* AT THE ABOVE POINT THE RATIO OF HT.TO DIA.=*,F8.3,*  VERT
            *.WALL HEIGHT=*,F8.3,*  COL.HEIGHT=*,F8.3)
 100  11     FORMAT(1H1)
 101         DO 15 I=1,N
 102  15     DN(I)=(D(I)-DMIN(I))/SPAN(I)
 104         CALL PENAL(F0,FP,FT,N,DN,1.0,GD)
 105         PRINT3,(GD(I),I=1,NC)
 112         HDR=1.5/(1.0-GD(1))
 113         PRINT10,HDR,H,HC
 114         COST1=F0
 115         IF(FT.LT.1.0E+25)GOTO17
 120         PRINT4
 121         ERR1=1.0
 122         ERR2=1.0
 123         GOTO 40
 124  17     DO 18 I=1,NC
 125         IF(GD(I).LT.0.1)FP=FP-1.0/GD(I)+10.0
 130  18     CONTINUE
 132         NPR=ALOG10(F0/FP)
 133         R=5.0*10.0**NPR
 134         RCHECK = R/1.0E+07
 135         NCHEKR=0
 136         FT=F0+R*FP
 137         PRINT5,F0,R,FT,COSTS,COSTC,COSTR
 140  20     CALL DFPOWL(N,DN,R,FT)
 141         CALL PENAL(F0,FP,FT,N,DN,R,GD)
 142         PRINT3,(GD(I),I=1,NC)
 147         PRINT5,F0,R,FT,COSTS,COSTC,COSTR
 150         PRINT6,NFE,NGE,NGS,NMA
 151         NCHEKR=NCHEKR+1
 152         GOTO(21,21,21,22,22,22,22,23,23,23,23,23,23,23,23,23,23,23),NCHEKR
 153  21     R=R/2.0
 154         GOTO 24
 155  22     R=R/5.0
 156         GOTO 24
 157  23     R=R/10.0
 160  24     CONTINUE
 161         DO 25 I=1,N
 162  25     D(I)=DMIN(I)+DN(I)*SPAN(I)
```

```
 ISN        SOURCE STATEMENT

 164        PRINT2,(D(I),I=1,N)
 171        HDR=1.5/(1.0-GD(1))
 172        PRINT10,HDR,H,HC
 173        ERR1=(COST1-FONEW)/FONEW
 174        COST1=FONEW
 175        ERR2=(FT-FONEW)/FONEW
 176        IF(ERR2.LT.EPS2)GOTO30
 201        PRINT8,ERR2,R
 202        GOTO 35
 203   30   IF(ERR1.LT.EPS1)GOTO40
 206        PRINT9,ERR1,R
 207   35   CONTINUE
 210        IF(R.LT.RCHECK)GOTO40
      C     IF(R.LE.1.0E-07)GOTO40
 213        PRINT198
 214        GOTO 20
 215   40   PRINT7,ERR1,ERR2,COST1,COSTS,COSTC,COSTR
 216        PRINT197,HDR
 217        PRINT199
 220  197   FORMAT(/* AT THE OPT.COST POIN THE RATIO OF HT.TO DIA.=*,F10.5/)
 221  198   FORMAT(1X,120(1H-),/)
 222  199   FORMAT(//1X,40(3H**-),//)
 223        GOTO 111
 224  200   STOP
 225        END
```


NO MESSAGES FOR ABOVE ASSEMBLY

ISN SOURCE STATEMENT

```
$IBFTC DFPOWL
      SUBROUTINE DFPOWL(N,D,R,FO)
C
C         DAVIDON-FLETCHER-POWELL METHOD
C           OPTIMUM  SEEKING  ALGORITHM
C
      DIMENSION D(16),S(16),G(16),G1(16),Q(16),HJ(16,16)
      DIMENSION GD(45),DMIN(15),SPAN(15)
      COMMON /NMBER/ NFE,NGE,NGS,NMA
      COMMON /PROB/NC,NCN
      COMMON /NORML/ DMIN,SPAN
      COMMON /CONCR/GCONCM,SIGCB,SIGC,SIGTB,SIGT,SIGS,SIGBON,SIGBR,AMODR
      COMMON /STEEL/ FS,FSH,FS1,FS2,ES,EC,AMODR1,PI
      COMMON /COST/FONEW,CC,CR,CAP,WTOP,TMT,W,WC,FI,DOPEN,TTA,AMUF,AMUE,
     *ALDAF,ALDAE,COSTS,CCSTC,COSTR,CRATIO,TTARUF,THR,ROPEN
      COMMON/DTFT/BCOV,CCCV,ELFACT,VCLEAR,WSEPF,WINDPR,ESEPF,SISCO3,FZ3
     *   ,WBETA
      NFE=0
      NGE=0
      NGS=0
      NMA=0
    1 FORMAT(* FUNC.VALUE=*,E15.7,/* AT STARTING VECTOR*,/2(8E15.7,/))
    2 FORMAT(* GRADIENT*,/5(8E16.7,/))
    3 FORMAT(* DIRECTION*,/5(8E16.7,/))
    4 FORMAT(* WITH STEP=*,E15.7,* FUNC.VALUE AND COSTS ARE*,4E15.7)
    5 FORMAT(* FUNC.VALUE=*,E15.7,* WITH STEP=*,E15.7,* AT NEW POINT *,/
     *2(8E15.7,/))
    7 FORMAT(* FORCED CONV.*,I3,* ITERATIONS PERFORMED*
     */* STEP CONV.CHECKED L1 AND L3 ARE *,2I5,* RESPECTIVELY*)
    8 FORMAT(* NORMAL CONV.*,I5,* ITERATIONS*)
    9 FORMAT(* X . . . FUNC.ERR =*,E16.7,* GOING TO RESTART . . . X*)
      ITER=0
      L1=0
      L3=0
      CALL PENAL(FO1,FP,FT1,N,D,R,GD)
      IF(FT1.GT.1.0E 25)RETURN
      FO=FT1
      PRINT1,FO,(D(I),I=1,N)
      CALL GRAD(D,N,G,R)
C     INITIALIZATION OF HJ MATRIX,DIR.S AND PRESERVATION OF G AS G1
   21 DO 30 I=1,N
      DO 25 J=1,N
   25 HJ(I,J)=0.0
   30 HJ(I,I)=1.0
   31 DO 40 I=1,N
      G1(I)=G(I)
      S(I)=0.0
      DO 40 J=1,N
   40 S(I)=S(I)-HJ(I,J)*G(J)
      FOLD=FO
      SS=0.0
      SSG=0.0
      DO 45 I=1,N
      SS=SS+S(I)*S(I)
   45 SSG=SSG+S(I)*G(I)
```

```
ISN         SOURCE STATEMENT

 71         SS=SQRT(SS)
       C    CHECK AS S TRASPOSE.DEL F/2.F
 72         ERR=ABS(SSG/2./FO)
 73         IF(ERR.LT.1.0E-10)GOTO80
 76         IF(SSG.LT.0.0)GOTO50
       C    OTHERWISE DIRECTION IS NOT USEFUL
101         GOTO 21
102   50    CONTINUE
       C    DIRECTION IS USEFUL
       C    INTERVAL FOR SEARCH IS BEING FIXED
       C    NO CARIABLE IS ASSUMED TO TAKE NEGATIVE VALUE
103         DIST=2.0
104         DO 52 I=1,N
105         S(I)=S(I)/SS
106         IF(S(I).GE.0.0)GOTO52
111         DISTEM=-D(I)/S(I)
112         IF(DISTEM.LT.DIST)DIST=DISTEM
115   52    CONTINUE
       C    AS PER NEED DIST MAY BE REDUSDED BY DIVD SUITABLY BY 10 OR100
       C    IN STR.OPT.PROB.SPECIALLY
117         DIST=DIST/10.0
120         IF(ABS(DIST).GT.1.0E-8)GOTO55
123         STEP=0.0
124         L3=L3+1
125         GOTO 56
126   55    CALL FIBO(D,N,S,DIST,STEP,FO,R)
127         IF(STEP.LT.1.0E-35)L3=L3+1
132         IF(STEP.LT.1.0E-05)L1=L1+1
135   56    CONTINUE
       CC
136         IF(L1.GE.5)GOTO70
141         IF(L3.GE.2)GOTO70
144         IF(STEP.LE.0.1E-35) GOTO21
       CC
       C    ITERATION LIMIT MAY BE REDUCED FOR SAVING TIME
147         ITER=ITER+1
150         IF(ITER.GT.20)GOTO70
       CC
153         CALL GRAD(D,N,G,R)
154         L2=0
       C    THIS CHECKS CONV.OF DESIGN VECTOR
       C    STEP LIMIT MAY BE CHANGED AS PER NEED
       CC
155         IF(ABS(STEP).LE.1.0E-35)GOTO65
       CC
160         DO 57 I=1,N
161         IF(ABS(STEP*S(I)).LT.1.0E-05)GOTO57
164         L2=L2+1
165   57    CONTINUE
167         IF(L2.EQ.0)GOTO75
172   65    DO 67 I=1,N
173   67    Q(I)=G(I)-G1(I)
175         CALL HASM(N,HJ,S,Q,STEP)
176         GOTO 31
177   70    PRINT7,ITER,L1,L3
```

```
    ISN       SOURCE STATEMENT

    200         ERR=ABS((FO-FOLD)/FO)
    201         GOTO 85
    202   75    ERR=ABS((FO-FOLD)/FO)
    203         IF(ERR.LT.0.0001)GOTO80
    206         PRINT9,ERR
    207         GOTO 21
    210   80    PRINT8,ITER
    211   85    PRINT5,FO,STEP,(D(I),I=1,N)
    216         RETURN
    217         END
```


NO MESSAGES FOR ABOVE ASSEMBLY

```
     ISN        SOURCE STATEMENT

       0 $IBFTC GRAD
       1         SUBROUTINE GRAD(D,N,G,R)
         C
         C          GRADIENT EVALUATION BY CENTRAL DIFFERENCE
         C
       2         DIMENSION D(16),G(16)
       3         DIMENSION GD(45),DMIN(15),SPAN(15),GD1(45),GD2(45)
       4         COMMON /NMBER/ NFE,NGE,NGS,NMA
       5         COMMON /PROB/NC,NCN
       6         COMMON /NORML/ DMIN,SPAN
       7         COMMON /CONCR/GCONCM,SIGCB,SIGC,SIGTB,SIGT,SIGS,SIGBON,SIGBR,AMOD
      10         COMMON /STEEL/ FS,FSH,FS1,FS2,ES,EC,AMODR1,PI
      11         COMMON /COST/FONEW,CC,CR,CAP,WTOP,TMT,W,WC,FI,DOPEN,TTA,AMUF,AMUE
                *ALDAF,ALDAE,COSTS,CCSTC,COSTR,CRATIO,TTARUF,THR,ROPEN
      12         COMMON/DTFT/BCOV,CCCV,ELFACT,VCLEAR,WSEPF,WINDPR,ESEPF,SISCO3,FZ3
                *   ,WBETA
      13         NGE=NGE+1
      14         CALL PENAL(FO,FP,FT,N,D,R,GD)
      15         DO 10 I=1,N
      16         ST=AMIN1(0.0001,D(I)/1000.0)
      17         D(I)=D(I)-ST
      20         CALL PENAL(FO1,FP1,FT1,N,D,R,GD1)
         C       MIDDLE DIFFERENCE
      21         D(I)=D(I)+ST+ST
      22         CALL PENAL(FO2,FP2,FT2,N,D,R,GD2)
      23         G(I)=(FO2-FO1)/(2.0*ST)
      24         DO 5 J=1,NC
      25  5      G(I)=G(I)-R*((GD2(J)-GD1(J))/(2.0*ST))/(GD(I)**2)
      27         D(I)=D(I)-ST
      30 10      CONTINUE
      32         RETURN
      33         END
```

CEG160 IBMAP ASSEMBLY GRAD

NO MESSAGES FOR ABOVE ASSEMBLY

CEG160

```
    ISN       SOURCE STATEMENT                          FORTRAN SOURCE LIST

      0  $IBFTC HASM
      1          SUBROUTINE HASM(N,HJ,S,Q,STEP)
         C
         C          UPDATING  OF  THE  HASIAN  MATRIX  FOR  DFP
         C
      2          DIMENSION HJ(16,16),S(16),Q(16)
      3          DIMENSION HN1(16),HMN(16,16),HNN(16,16)
      4          COMMON /NMBER/ NFE,NGE,NGS,NMA
      5          NMA=NMA+1
         C       REASSEMBLY OF HASSIAN MATRIX
         C       (JQ+1)=(JQ)+(MQ)+(NQ)
         C       QQ=GQ+1-GQ
         C       (MQ)=ALFASTAR*(SQ*SQ)/SQ*QQ
         C       (NQ)=-((JQ)*QQ)*(JQ)*QQ/QQ(JQ)QQ
      6          HMD=0.0
      7          DO 9 I=1,N
     10    9     HN1(I)=0.0
     12          DO 10 I=1,N
     13          HMD=HMD+S(I)*Q(I)
     14          DO 10 J=1,N
     15          HN1(I)=HN1(I)+HJ(J,I)*Q(J)
     16          HMN(I,J)=S(I)*S(J)
     17   10     CONTINUE
     22          HND=0.0
     23          DO 20 I=1,N
     24          HND=HND+HN1(I)*Q(I)
     25          DO 20 J=1,N
     26   20     HNN(I,J)=HN1(I)*HN1(J)
     31          DO 30 I=1,N
     32          DO 30 J=1,N
     33   30     HJ(I,J)=HJ(I,J)+STEP*HMN(I,J)/HMD-HNN(I,J)/HND
     36          RETURN
     37          END
```

CEG160   IBMAP ASSEMBLY HASM

NO MESSAGES FOR ABOVE ASSEMBLY

ISN SOURCE STATEMENT

```
$IBFTC GOLDEN
      SUBROUTINE FIBO(D,N,S,DIST,STEP,FO,R)
C
C         GOLDEN SECTION SEARCH TECH.FOR LINEAR MINMIZATION
C
      DIMENSION D(16),S(16),D1(16),D2(16),DO(16)
      DIMENSION GD(45),DMIN(15),SPAN(15)
      COMMON /NMBER/ NFE,NGE,NGS,NMA
      COMMON /PROB/NC,NCN
      COMMON /NORML/ DMIN,SPAN
      COMMON /CONCR/GCONCM,SIGCB,SIGC,SIGTB,SIGT,SIGS,SIGBON,SIGBR,AM
      COMMON /STEEL/ FS,FSH,FS1,FS2,ES,EC,AMODR1,PI
      COMMON /COST/FONEW,CC,CR,CAP,WTOP,TMT,W,WC,FI,DOPEN,TTA,AMUF,AM
     *ALDAF,ALDAE,COSTS,CCSTC,COSTR,CRATIO,TTARUF,THR,ROPEN
      COMMON/DTFT/BCOV,CCCV,ELFACT,VCLEAR,WSEPF,WINDPR,ESEPF,SISCO3,F
     *  ,WBETA
      NGS=NGS+1
      NCHECK=0
      DO 40 I=1,N
   40 DO(I)=D(I)
C     GOLDEN SEARCH
      LOGICAL ONE,TWO
      R1=0.618034
      R2=1.618034
   41 CONTINUE
      ONE=.FALSE.
      TWO=.FALSE.
      ITER=0
   51 ITER=ITER+1
      ALFA1=DIST/R2
      ALFA2=DIST-ALFA1
      DO 55 I=1,N
      D1(I)=D(I)+ALFA1*S(I)
   55 D2(I)=D(I)+ALFA2*S(I)
      IF(ONE)GOTO56
      CALL PENAL(FC,FP,F1,N,D1,R,GD)
   56 IF(TWO)GOTO57
      CALL PENAL(FC,FP,F2,N,D2,R,GD)
   57 CONTINUE
      IF(F1.LT.1.0E 20)GOTO59
      IF(F2.LT.1.0E 20)GOTO58
      DIST=ALFA2
      GOTO 41
   58 DIST=ALFA1
      GOTO 41
   59 IF(ITER.EQ.10)GOTO75
      IF(F1.GT.F2)GOTO65
      DO 60 I=1,N
   60 D(I)=D2(I)
      F2=F1
      TWO=.TRUE.
      ONE=.FALSE.
      GOTO 70
   65 F1=F2
      ONE=.TRUE.
```

```
ISN       SOURCE STATEMENT

              TWO=.FALSE.
       70     DIST=ALFA1
              GOTO 51
       75     FMIN=AMIN1(F1,F2)
              DO 76 I=1,N
              L=I
              IF(ABS(S(I)).GT.0.1E-30)GOTO77
       76     CONTINUE
       77     I=L
              IF(FMIN.GT.F0)GOTO100
              IF(FMIN.EQ.F2)GOTO85
              STEP=(D1(I)-D0(I))/S(I)
              DO 80 I=1,N
       80     D(I)=D1(I)
              F0=F1
              RETURN
       85     STEP=(D2(I)-D0(I))/S(I)
              DO 90 I=1,N
       90     D(I)=D2(I)
              F0=F2
              RETURN
      100     CONTINUE
              DO 102 I=1,N
      102     D(I)=D0(I)
              NCHECK=NCHECK+1
              IF(NCHECK.GT.2)GOTO117
              IF(FMIN.EQ.F1)GOTO104
              DIST=(D2(L)-D0(L))/S(L)
              GOTO 110
      104     DIST=(D1(L)-D0(L))/S(L)
      110     IF(DIST.LE.1.0E-8)GOTO117
              GOTO 41
      117     STEP=0.0
      120     RETURN
              END
```

CEG160 IBMAP ASSEMBLY GOLDEN

NO MESSAGES FOR ABOVE ASSEMBLY

CEG160 FORTRAN SOURCE LIST

```
 ISN        SOURCE STATEMENT

   0 $IBFTC PENAL
   1        SUBROUTINE PENAL(FO,FP,FT,N,DN,R,GD)
     C
     C         INTERIOR  PENALITY  FUNCTION
     C
   2        DIMENSION D(15),DN(15),DMIN(15),SPAN(15),GD(45)
   3        COMMON /NMBER/ NFE,NGE,NGS,NMA
   4        COMMON /PROB/NC,NCN
   5        COMMON /NORML/ DMIN,SPAN
   6        COMMON /CONCR/GCONCM,SIGCB,SIGC,SIGTB,SIGT,SIGS,SIGBON,SIGBR,AMODR
   7        COMMON /STEEL/ FS,FSH,FS1,FS2,ES,EC,AMODR1,PI
  10        COMMON /COST/FONEW,CC,CR,CAP,WTOP,TMT,W,WC,FI,DOPEN,TTA,AMUF,AMUE,
           *ALDAF,ALDAE,COSTS,CCSTC,COSTR,CRATIO,TTARUF,THR,ROPEN
  11        COMMON/DTFT/BCOV,CCCV,ELFACT,VCLEAR,WSEPF,WINDPR,ESEPF,SISCO3,FZ3
           *  ,WBETA
  12        COMMON /SHAPE/ H,HC
  13        NFE=NFE+1
  14        PI=4.0*ATAN(1.0)
  15        DO 10 I=1,N
  16   10   D(I)=DMIN(I)+DN(I)*SPAN(I)
  20        CALL ANLSIS(N,D,GD,FO)
     C      INCLUDES CAL.OF LOAD,STRESS,AND CONS.OTHER THAN ON +VENESS ANDSPN
     C      ALSO INCLUDES COST CAL.
     CC
     CC
  21        DO 20 I=1,N
  22        II=NCN+I
  23   20   GD(II)=DN(I)*(1.0-DN(I))
  25        SUM=0.0
  26        DO 30 I=1,NC
  27        IF(GD(I).LT.0.0)GOTO40
  32        IF(GD(I).EQ.0.0)GD(I)=1.0E-08
  35   30   SUM=SUM+1.0/GD(I)
  37        FP=R*SUM
  40        FT=FO+FP
  41        FONEW=FO
  42        RETURN
  43   40   FT=1.0E 30
  44        RETURN
  45        END
```

CEG160 IBMAP ASSEMBLY PENAL

NO MESSAGES FOR ABOVE ASSEMBLY

```
   ISN        SOURCE STATEMENT

    C  $IBFTC ANLSIS
     1        SUBROUTINE ANLSIS(N,X,G,FO)
       C
       C          EVALUATION - LOADS,STRESSES,COST  OF  THE
       C                             SILO
       C          AND  CONSTRAINTS  OTHER  THAN  BOUNDS  ON  VARIABLES
       C
     2        DIMENSION X(15) ,G(45),CLOD(2),CLBM(2)
     3        COMMON /PROB/NC,NCN
     4        COMMON /CONCR/GCONCM,SIGCB,SIGC,SIGTB,SIGT,SIGS,SIGBON,SIGBR,AMODR
     5        COMMON /STEEL/ FS,FSH,FS1,FS2,ES,EC,AMODR1,PI
     6        COMMON /COST/FONEW,CC,CR,CAP,WPOT,TMT,W,WC,FI,DOPEN,TTA,AMUF,AMUE,
             *ALDAF,ALDAE,COSTS,CCSTC,COSTR,CRATIO,TTARUF,THR,ROPEN
     7        COMMON/DTFT/BCOV,CCCV,ELFACT,VCLEAR,WSEPF,WINDPR,ESEPF,SISCO,FZF
             *  ,WBETA
    10        COMMON /SHAPE/ H,HC
    11        D=X(1)
    12        TW=X(2)
    13        TH=X(3)
    14        HR=X(4)
    15        BR=X(5)
    16        DCOL=X(6)
    17        ASW1=X(7)
    20        ASW2=X(8)
    21        ASH1=X(9)
    22        ASH2=X(10)
    23        ASR1=X(11)
    24        ASR2=X(12)
    25        ASR3=X(13)
    26        ASCS=X(14)
    27        ASCL=X(15)
    30        CICCL=PI*DCOL**4/64.0
    31        ACOL=PI*DCOL*DCOL/4.0
    32        AR=HR*BR
    33        RMIY=BR*HR**3/12.0
    34        RMR=(D+TW)/2.0
    35        R1=RMR-BR/2.0
    36        R2=RMR+BR/2.0
    37        WTOP=D*WPOT
    40        EE=(HR+TW*SIN(TTA)-TH)/2.0
       C      SHAPE  AND  PRESSURE
    41        HHOP=(D-DOPEN)*TAN(TTA)/2.0
    42        HCLEAR=D*TAN(FI)/4.0
    43        H=(CAP*1000.0/W-PI*HHOP*(D*D+DOPEN*DOPEN+D*DOPEN)/12.0)/(PI*D*D/
             14.0)+HCLEAR
    44        HT=H+HHOP
       C      DEEP  SILO  CRITERIA
    45        G(1)=1.0-1.5*D/H
       C      LIMIT  ON  THICKNESS
    46        G(2)=1.0-0.1/TW-D/(TW*120.0)
       C      FILLING PRESSURE  MAX. AT  LOWEST  POINT
       C      EMPTING PR.MAX.AT AMIN1(1.2*D,0.75*HT) ABOVE LOWEST POINT
       C      H HYDRA.=R
    47        R=D/4.0
    50        PWMAX=W*R
```

```
  ISN        SOURCE STATEMENT

  133        WT2=WHOPG+PI*D*(WC*(H*TW+BR*HR)+WTOP)+WHOPC
  134        WT=WT1
         C   EARTHQUAKE AND WIND FORCES
         C   DAMPING FACTOR IS TAKEN AS  5  PER.
  135        HC= VCLEAR+HHOP-HR
  136        HCOL=HC*ELFACT
  137        AMASS=WT/981.0
  140        AKEQ=6.0*(3.0*EC*CICOL/HC**3)*100.0
  141        TNAT=2.0*PI/(SQRT(AMASS/AKEQ))
  142        CALL SPECTR(TNAT,AVACCL)
  143        PEARTH=ESEPF*AMASS*(FZF*WBETA)*AVACCL
  144        PWIND=WSEPF*WINDPR*(D*H+HHOP*(D+DOPEN)/2.0)
  145        HORZF=AMAX1(PEARTH,PWIND)
         C   VERT.W.  VERT.REINF.  FOR  VERT.LOADS AND HORZ.LOADS ETC.
  146        TFWF=AMAX1(TFWF,TFWE)
  147        STRESW=(WTOP+H*TW*WC)/(TW*(1.+AMODR1*ASW2))
  150        STRESG=TFWF/(TW*(1.C+AMODR1*ASW2))
  151        STRESH=2.0*HORZF*H/(PI*TW*(1.0+AMODR1*ASW2)*D**2)
  152        G(6)=1.0-(STRESH-STRESW)/(SIGT*10000.0)
  153        G(7)=1.0-(STRESG+STRESW)/(1500.0*GCONCM)
  154        G(8)=1.0-(STRESH+STRESW+STRESG)/(2C00.0*GCONCM)
         C   HOPPER  DESIGN
  155        FMDES=AMAX1(FM1*DM/D,FM2)
  156        FHHDES=AMAX1(FHUP1*DM/D,FHUP2)
         C   MERIDINAL  RING
  157        AEQ=TH*(1.0+AMODR1*ASH1)
  160        G(9)=1.0-FMDES/(AEQ*SIGT*10000.0)
  161        G(10)=1.0-(FMDES+3.0*ES*ASH1*TW)/(AEQ*13333.3*SIGT)
  162        G(11)=1.0-FMDES/(FS1*ASH1*10000.0)
         C   CIRCULAR  OR  HOOP  REINF.
  163        AEQ=TH*(1.0+AMODR1*ASH2)
  164        G(12)=1.0-FHHDES/(AEQ*SIGT*10000.0)
  165        G(13)=1.0-(FHHDES+3.0*ES*ASH2*TH)/(AEQ*13333.3*SIGT)
  166        G(14)=1.0-FHHDES/(FS1*ASH2*10000.0)
         C   INTER ACTION BETWEEN COLUMN AND RING GIRDER
  167        TMT=EE*FM1
  170        REAL K1,K2,K3,K4,K5,K6,K7,K8,K9
  171        DATA K1,K2,K3,K4,K5,K6,K7,K8,K9/
            *     .083333,.04797,-.01482,.00751,-.866,-1.0,-.9549,.00151,.2982/
  172        DATA DKK,DDKK / 0.003364,1.1153 /
  173        HHGG=AMAX1(BR,HR)
  174        BBSS=AMIN1(BR,HR)
  175        RATIO=HHGG/BBSS
         C   RESTRICTION  ON  RING  GIRDER  SIZE
  176        G(15)=(1.0-1.0/RATIO)*(1.0-RATIO/4.0)
  177        CALL TOPRO(RATIO,ALFA,BETA,GAMA)
  200        A11=(RMR**3*DKK*0.5/RMIY + HC**3/(3.0*CICOL))
  201        A12=(-HC**2*0.5/CICOL)
  202        A21= -A12
  203        A22=(RMR*PI*DDKK/(6.8*ALFA*BR**4) - HC/CICOL)
  204        B1=-SX1*RMR**2/AR
  205        B2=-12.0*TMT*RMR/(HR**3*ALOG(R2/R1))
  206        DEN = (A11*A22-A21*A12)
  207        HA= (B1*A22-B2*A12)/DEN
  210        TMTA= (A11*B2-A21*B1)/DEN
```

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  ISN        SOURCE STATEMENT

  211        COLCD1=WT/6.0
  212        SFRG1=K1*WT
  213        SFRG3=K2*WT
  214        BMMAX1=K3*WT*RMR + K5*TMTA + TMT*RMR
  215        BMMAX2=K4*WT*RMR + K6*TMTA + TMT*RMR
  216        BMMAX3=K7*TMTA + TMT*RMR
  217        TMMAX1=0.5*TMTA
  220        TMMAX3=K8*WT*RMR+K9*TMTA
         C   1 ,2 ,3  . . REFER  TO  SUP.,MID.,MAX TORS  POINTS  RESPECTIVELY
         C   RING  BEAM  DES.
  221        ANCR=1.0/(1.0+FS2/(AMODR*SIGCB))
  222        AJCR=1.0-ANCR/3.0
  223        QCR=ANCR*AJCR*SIGCB/2.0
  224        TMMAX=TMMAX3
  225        IF(BMMAX3.LT.0.0) BMMAX1=AMIN1(BMMAX1,BMMAX3)
  230        IF(BMMAX3.GT.0.0) BMMAX2=AMAX1(BMMAX2,BMMAX3)
  233        BMMAX=AMAX1(ABS(BMMAX1),BMMAX2)
  234        QPQD1=SFRG1/(BR*AJCR*(HR-BCOV)) + TMMAX1/(BETA*BBSS**3)
  235        QPQD3=SFRG3/(BR*AJCR*(HR-BCOV)) + TMMAX3/(BETA*BBSS**3)
  236        G(16)=1.0-AMAX1(QPQD1, QPQD3)/(40000.0*SIGS)
  237        ASR1B=ABS(BMMAX1/(FS2*AJCR*(HR-BCOV)))/10000.0
  240        ASR2B=ABS(BMMAX2/(FS2*AJCR*(HR-BCOV)))/10000.0
  241        ASR3S1=SFRG1/(FS2*AJCR*(HR-BCOV))/10000.0
  242        ASR3S3=SFRG3/(FS2*AJCR*(HR-BCOV))/10000.0
  243        ASR3T = TMMAX/(0.8*FS2*(BR-1.5*BCOV)*(HR-1.5*BCOV))/10000.0
  244        AS12T=ASR3T*(HR-1.5*BCOV)/2.0
  245        ASR1R=(ASR1B+AS12T)/AR
  246        ASR2R=(ASR2B+AS12T)/AR
  247        ASR3T1=TMMAX1/(0.8*FS2*(BR-1.5*BCOV)*(HR-1.5*BCOV))/10000.0
  250        ASR3T3=ASR3T
  251        ASRST=AMAX1(ASR3S1+ASR3T1 , ASR3S3+ASR3T3)
  252        ASR3R=ASRST*(HR+BR-3.0*BCOV)/AR
  253        G(17)=1.0-ASR1R/ASR1
  254        G(18)=1.0-ASR2R/ASR2
  255        G(19)=1.0-ASR3R/ASR3
  256        RCOMP=SX1*RMR
  257        P=RCOMP
  260        BCHR=BCOV/HR
         C   CHECK  FOR  ECCENTRICITY
  261        ERA=HR*BR*(1.0+AMODR1*(ASR1+ASR2))
  262        IF(BMMAX2.LT.0.0)PRINT921,BMMAX2
  265        EXEN=BMMAX2/P
  266        IF(EXEN.GT.(HR/6.0))GOTO120
         C   DES. ON  NO  CRACK  BASIS - SMALL  ECCENTRICITY
  271        AN=(.5+AMODR1*(ASR1*BCHR+ASR2*(1.-BCHR)))/(1.+AMODR1*(ASR1+ASR2))
  272        ERI=(1./12.+(.5-AN)**2+AMODR1*(ASR1*(AN-BCHR)**2+ASR2*(1.-BCHR-AN
            ***2))*BR*HR**3
  273        G(20)=1.0+(-P/(ERA*SIGC)-BMMAX2*AN*HR/(ERI*SIGCB))/10000.0
  274        G(21)=1.0+(P/ERA-BMMAX2*(1.-AN)*HR/ERI)/(SIGTB*10000.0)
  275        GOTO 123
  276   120  ACONS=6.*((AMODR1*ASR1*BCHR+AMODR*ASR2*(1.-BCHR))*(EXEN/HR-.5)+(A
            OODR1*ASR1*BCHR**2+AMODR*ASR2*(1.-BCHR)**2))
  277        BCONS=3.*EXEN/HR-1.5
  300        CCONS=6.*((EXEN/HR-.5)*(ASR1*AMODR1+ASR2*AMODR)+ASR1*AMODR1*BCHR+A
            SSR2*AMODR*(1.-BCHR))
```

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ISN        SOURCE STATEMENT

301              AN=0.5
302              DO 121  I=1,10
303              ANNEW=ACONS/(AN**2+BCONS*AN+CCONS)
304              DIFF=ABS(AN-ANNEW)
305              AN=(AN+ANNEW)/2.0
306              IF((DIFF/AN).LT.0.0001)GOTO122
311       121    CONTINUE
313       122    CSTRES=P*(EXEN/HR+.5-BCHR)/(.5*AN*(1.-BCHR-AN/3.)+AMODR1*ASR1*(1.-
                BBCHR/AN)*(1.-2.*BCHR))/(BR*HR*10000.0)
314              G(20)=1.0-CSTRES/SIGCB
315              G(21)=1.0-AMODR*CSTRES*(1.-BCHR-AN)/(AN*FS2)
316       123    IF(BMMAX1.GT.0.0)PRINT922,BMMAX1
321              EXEN=ABS(BMMAX1/P)
322              IF(EXEN.GT.(HR/6.0))GOTO124
325              AN=(.5+AMODR1*(ASR2*BCHR+ASR1*(1.-BCHR)))/(1.+AMODR1*(ASR1+ASR2))
326              ERI=(1./12.+(.5-AN)**2+AMODR1*(ASR2*(AN-BCHR)**2+ASR1*(1.-BCHR-AN)
                ***2))*BR*HR**3
327              G(22)=1.0+(-P/(ERA*SIGC)+BMMAX1*AN*HR/(ERI*SIGCB))/10000.0
330              G(23)=1.0+(P/ERA+BMMAX1*(1.-AN)*HR/ERI)/(SIGTB*10000.0)
331              GOTO 128
332       124    ACONS=6.*((AMODR1*ASR2*BCHR+AMODR*ASR1*(1.-BCHR))*(EXEN/HR-.5)+(AM
                ODDR1*ASR2*BCHR**2+AMODR*ASR1*(1.-BCHR)**2))
333              BCONS=3.*EXEN/HR-1.5
334              CCONS=6.*((EXEN/HR-.5)*(ASR2*AMODR1+ASR1*AMODR)+ASR2*AMODR1*BCHR+A
                SSR1*AMODR*(1.-BCHR))
335              AN=0.5
336              DO 125  I=1,10
337              ANNEW=ACONS/(AN**2+BCONS*AN+CCONS)
340              DIFF=ABS(AN-ANNEW)
341              AN=(AN+ANNEW)/2.0
342              IF((DIFF/AN).LT.0.0001)GOTO126
345       125    CONTINUE
347       126    CSTRES=P*(EXEN/HR+.5-BCHR)/(.5*AN*(1.-BCHR-AN/3.)+AMODR1*ASR2*(1.-
                BBCHR/AN)*(1.-2.*BCHR))/(BR*HR*10000.0)
350              G(22)=1.0-CSTRES/SIGCB
351              G(23)=1.0-AMODR*CSTRES*(1.-BCHR-AN)/(AN*FS2)
352       128    CONTINUE
        CC
        C        SUPPORTING  COL.
353              RATIO=HCOL/DCOL
354              IF(RATIO.LE.15.0)GOTO130
357              CRC=1.5-RATIO/30.0
360              GOTO 135
361       130    CRC=1.0
362       135    C1=CRC*SIGC
363              C2=CRC*SIGCB
364              C3=CRC*FSH
365              FC=CRC*GCONCM
366              COLOD2=COLOD1-CAP*1000.0/6.0
        C        DUE  TO  HORZ. FORCE
367              COLODH=HORZF*(H/2.0+HR)/(RMR*(2.0+4.0*SIN(PI/6.)**2))
370              CLODSW=WC*ACOL*HC
371              Z=PI*DCOL*(DCOL**2/32.+AMODR1*ASCL*(DCOL-2.*CCOV)**2/8.0)
372              ACOLEF=ACOL*(1.+AMODR1*(ASCL+2.*ASCS))
        C        HERE  B.M.FOR COL IS TOO SMALL SO NOT CONSIDERED
```

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ISN      SOURCE STATEMENT

         DIV=AMIN1((ACOLEF*SIGT),(ASCL*FS2+2.0*ASCS*FSH)*1.333*ACOL)
         G(24)=1.0-(COLODH-CCLOD2)/(DIV*10000.0)
   CC
         CLOD(1)=COLOD1+COLODH
         CLBM(1)=ABS(TMTA)
         CLOD(2)=CLOD(1)+CLODSW
         CLBM(2)=ABS(HC*(HA+HORZF/6.0)-TMTA)
         G(25)=1.0-(SIGC*((1.-2.0*CCOV/DCOL)**2-ASCL)+2.0*FSH*ASCS)/(.5*FC)
         G(26)=1.0-3.0*CLBM(1)*ACOLEF/(5.0*CLOD(1)*Z)
         G(27)=1.0-(CLOD(1)/(ACOLEF*SIGC)+CLBM(1)/(Z*SIGCB))/10000.0
         G(28)=1.0 - (C1*((1.-2.0*CCOV/DCOL)**2-ASCL)+2.0*C3 *ASCS)/(.5*FC)
         G(29)=1.0-3.0*CLBM(2)*ACOLEF/(5.0*CLOD(2)*Z)
         G(30)=1.0-(CLOD(2)/(ACOLEF*C1) + CLBM(2)/(Z*C2))/10000.0
   CC
         CR1=CRATIO-1.0
         HROCF=(D-ROPEN)*TAN(TTARUF)/2.0
         DMR=DM
   C     PERCT.INCR.IN COST - PIC - DUE TO INCR.IN CONSTR.HT.ABOVE HFC
         HFC=3.0
         PIC=0.01
         PICC=(HC-HFC)*PIC/2.0
         PICR=(HC+HR/2.0-HFC)*PIC
         PICV=(HC+HR+H/2.0-HFC)*PIC
         PICH=(HC+HR-HFC-HHOP/2.0)*PIC
         PICRUF=(HC+HR+H+HROCF/2.0-HFC)*PIC
         COSTC=CC*(6.*ACOL*(HFC+(HC-HFC)*(1.+PICC))*(1.+CR1*(ASCL+ASCS)))
         COSTR=CC*(1.+PICR)*PI*(2.*RMR*AR*(1.+CR1*(ASR1+ASR2+ASR3)))
         COSTS=CC*PI*((1.+PICV)*(D+TW)*TW*H*(1.+CR1*(ASW1+ASW2))+(1.+PICH)*
        *DM*TH*HHOP/SIN(TTA)*(1.+CR1*(ASH1+ASH2)))
        * +CC*PI*(1.+PICRUF)*DMR*THR*HROOF/SIN(TTARUF)*(1.0+CR1*0.006)
         FO=COSTC+COSTR+COSTS
    901  FORMAT(1X,F10.2,6E17.7)
    902  FORMAT(1X,120(1H-))
    903  FORMAT(* MAX.HORZ.FIL  MAX.EMT.AND DES.PRS.ARE*,3E17.7,* COR. HTS
        1 *,2F10.3)
    904  FORMAT(1X,6E17.7)
    906  FORMAT(* WT.OF HOP.GRAIN AND SILO-HOP *,2E17.7
        */* MERIDINAL AND RING FORCES *,4E17.7)
    907  FORMAT(* MERIDINAL AND HOOP FORCES AT MIDHOPPER HT.*,4E17.7)
    911  FORMAT(* WIND FACTORA AND FORCE ARE*,3E17.7,
        */* EARTHQUAKE FACTS.AND FORCE *,6E17.7)
    920  FORMAT(//*  LARGE  ECCENTRICITY*)
    921  FORMAT(* . . X X MID. B. M.=*,E15.7,* X X . . *)
    922  FORMAT(* . . X X SUP. B. M.=*,E15.7,* X X . . *)
    923  FORMAT(* . . . .  AN = *,E15.7)
    999  FORMAT(1X,40(3H**-))
         RETURN
         END
```

CEG160 . IBMAP ASSEMBLY ANLSIS

NO MESSAGES FOR ABOVE ASSEMBLY

```
CEG160                                                      FORTRAN SOURCE LIST
    ISN        SOURCE STATEMENT

      0 $IBFTC SPECTR
      1        SUBROUTINE  SPECTR(T,ACCL)
         C     SPECTRA FOR DAMPING FACTOR = 5 +ER FIG.15  P.VI.1.16 N.B.C.OF I.70
      2        IF(T.GE.0.4.AND.T.LE.0.8)GOTO1
      5        IF(T.GE.0.8.AND.T.LE.1.2)GOTO2
     10        IF(T.GE.1.2.AND.T.LE.1.6)GOTO3
     13        IF(T.GE.1.6.AND.T.LE.2.0)GOTO4
     16        IF(T.GE.2.0.AND.T.LE.2.4)GOTO5
     21        IF(T.GE.2.4.AND.T.LE.2.8)GOTO6
     24        IF(T.GT.2.8)GOTO8
     27        PRINT7,T
     30        STOP
     31   1    ACCL=175.0-50.0*(T-0.4)/0.4
     32        RETURN
     33   2    ACCL=125.0-35.0*(T-0.8)/0.4
     34        RETURN
     35   3    ACCL=90.0-22.0*(T-1.2)/0.4
     36        RETURN
     37   4    ACCL=68.0-11.0*(T-1.6)/0.4
     40        RETURN
     41   5    ACCL=57.0-7.0*(T-2.0)/0.4
     42        RETURN
     43   6    ACCL=50.0-3.0*(T-2.4)/0.4
     44        RETURN
     45   7    FORMAT(* NATURAL PERIOD = *,E17.7,* IS OUT OF RANGE*)
     46   8    ACCL=47.0
     47        RETURN
     50        END
CEG160                                                      IBMAP ASSEMBLY SPECTR


   NO MESSAGES FOR ABOVE ASSEMBLY
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```
CEG160
   ISN        SOURCE STATEMENT                      FORTRAN SOURCE LIST

        $IBFTC TORSON
              SUBROUTINE TOPRO( AM,ALFA,BETA,GAMA)
        C     TABLE III   SAF  PAP
              IF(AM.GE.1.0.AND.AM.LE.1.5)GOTO1
              IF(AM.GE.1.5.AND.AM.LE.2.0)GOTO2
              IF(AM.GE.2.0.AND.AM.LE.3.0)GOTO3
              IF(AM.GE.3.0.AND.AM.LE.4.0)GOTO4
              RETURN
        1     AMM=(AM-1.0)/0.5
              ALFA=0.140+0.154*AMM
              BETA=0.204+0.138*AMM
              GAMA=1.000-0.141*AMM
              RETURN
        2     AMM=(AM-1.5)/0.5
              ALFA=0.294+0.163*AMM
              BETA=0.346+0.147*AMM
              GAMA=0.859-0.064*AMM
              RETURN
        3     AMM=(AM-2.0)
              ALFA=0.457+0.333*AMM
              BETA=0.493+0.308*AMM
              GAMA=0.795-0.042*AMM
              RETURN
        4     AMM=AM-3.0
              ALFA=0.79+0.333*AMM
              BETA=0.801+0.349*AMM
              GAMA=0.753-0.008*AMM
              RETURN
        5     FORMAT(* RATIO OF RING GIRDER DEPTH TO WIDTH = *,E17.7,* GOE
             1OF RANGE*)
              END
CEG160                                              IBMAP ASSEMBLY TORSON

   NO MESSAGES FOR ABOVE ASSEMBLY
CEG160                                              IBLDR -- JOB   000000

                          M E M O R Y   M A P

STEM, INCLUDING IOCS                                  00000 THRU  12251

LE BLOCK ORIGIN                                       12260

    NUMBER OF FILES -       9

    1.   S.FBIN                          12260
    2.   S.FBOU                          12303
    3.   S.FBPP                          12326
    4.   FTC00.                          12351
    5.   FTC01.                          12374
    6.   FTC02.                          12417
    7.   FTC03.                          12442
    8.   FTC04.                          12465
    9.   FTC99.                          12510

IECT PROGRAM                                          12533 THRU  40722

    1.   DECK 'INPUT '  *                12533
    2.   DECK 'DEPOWL'  *                14534
```